Joint Search for Muon Neutrino Disappearance at $\Delta m^2 \sim 1\ eV^2$ with SciBooNE and MiniBooNE

April 29, 2011

Fermilab Wine and Cheese Seminar

Yasuhiro Nakajima (Kyoto U./LBNL)

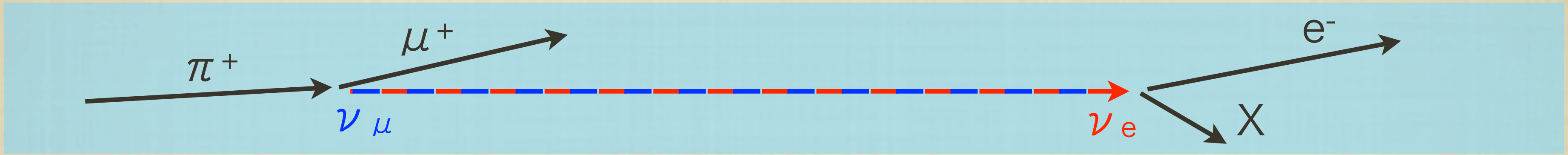
Overview

- Introduction
  - Neutrino oscillation
  - Short-baseline ν_μ disappearance
- Experiments: SciBooNE and MiniBooNE
- SciBooNE-MiniBooNE joint ν_μ disappearance analysis
- Results

Introduction

Neutrino Oscillation

Neutrinos can change their flavors if neutrinos have finite masses and if the weak and mass eigenstates are mixed



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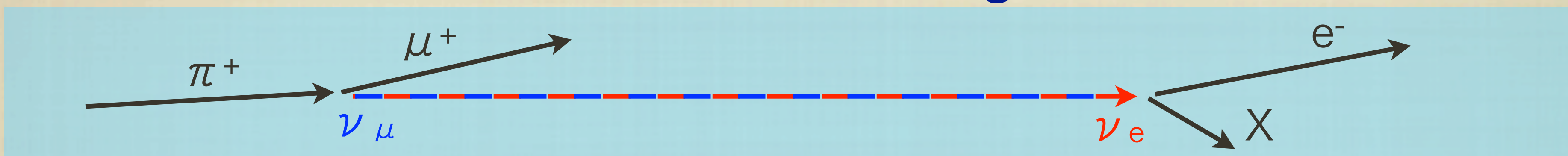

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

Weak eigenstate (α = e, μ, τ)

Mass eigenstate (i = 1, 2, 3)

MNS mixing matrix

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Two neutrino case:

$$\boxed{P(\nu_\alpha \to \nu_\beta) \quad = \quad |\langle \nu_\beta | \nu(t) \rangle|^2 = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)}$$

θ	: mixing angle
Δm^2	: mass squared difference
L [km]	: the distance traveled
E (GeV)	: the energy of neutrino

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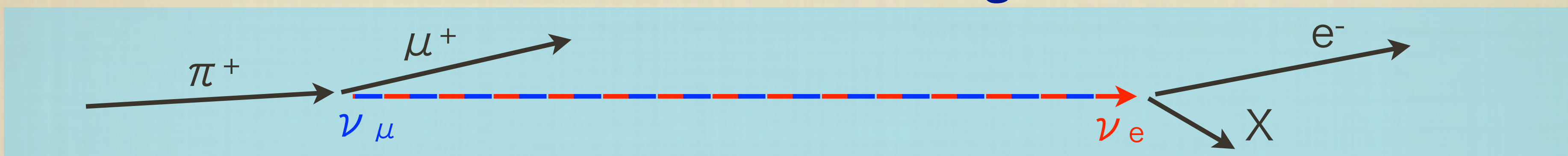

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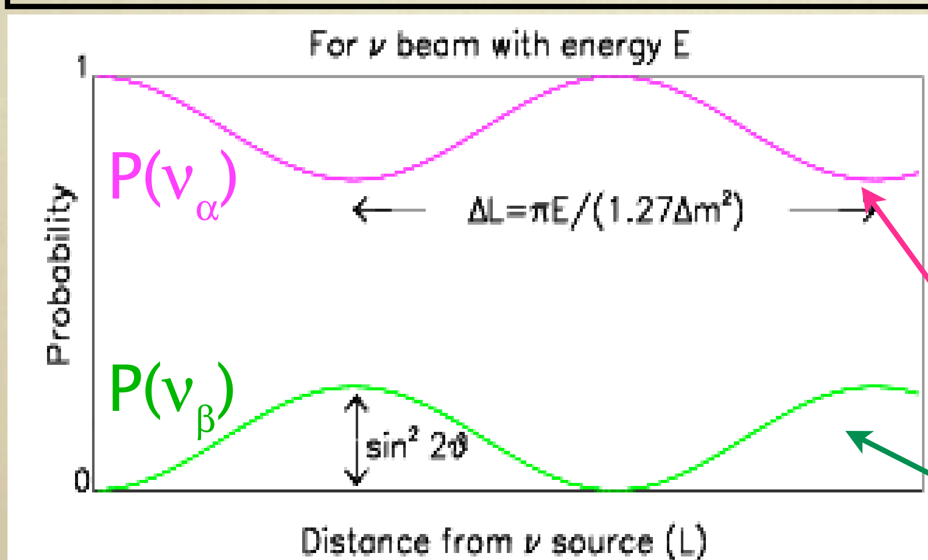

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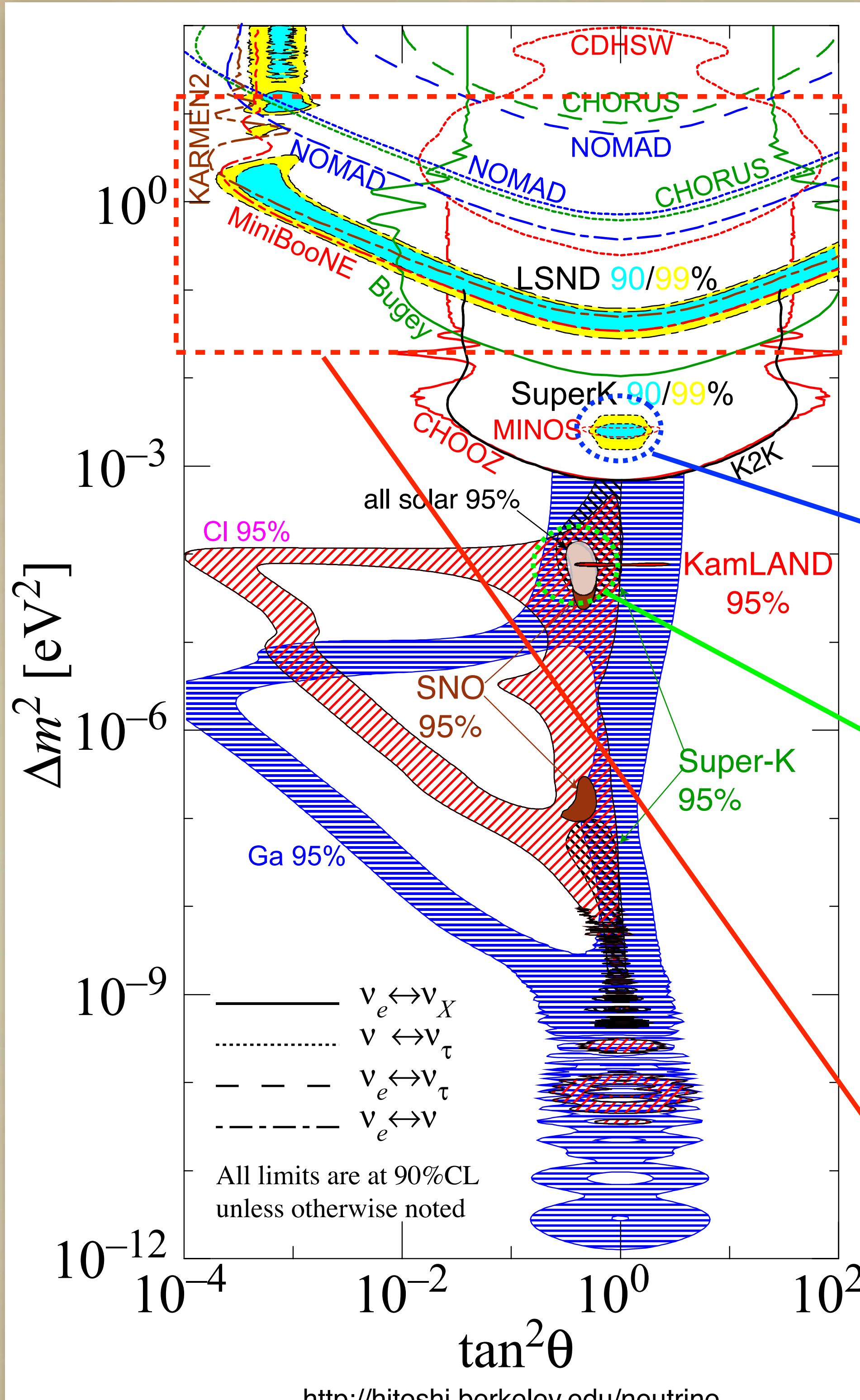
L [km]	: the distance traveled
E (GeV)	: the energy of neutrino

disappearance of ν_α

appearance of ν_β

Observed Neutrino Oscillations



- Atmospheric region: $\Delta m^2 \sim 10^{-3}$ eV^2
  - Super-K, K2K, MINOS, etc
- Solar region: $\Delta m^2 \sim 10^{-5}$ eV^2
  - SNO, Super-K, KamLAND, etc

Only 2 Δm^2 regions are allowed in the current SM with 3 neutrino generations

However, there is one more region claimed by the LSND experiment at $\Delta m^2 \sim 1$ eV^2

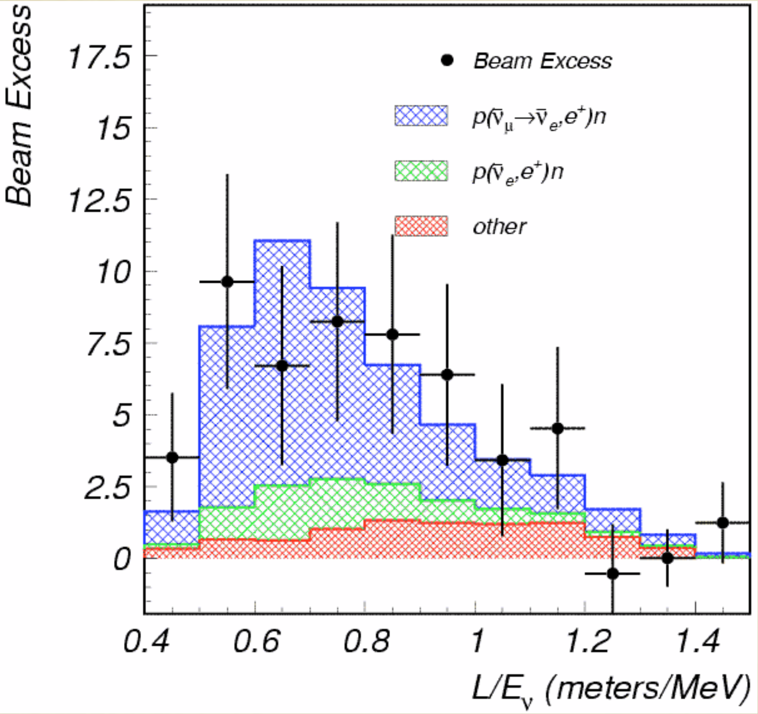
The LSND Signal

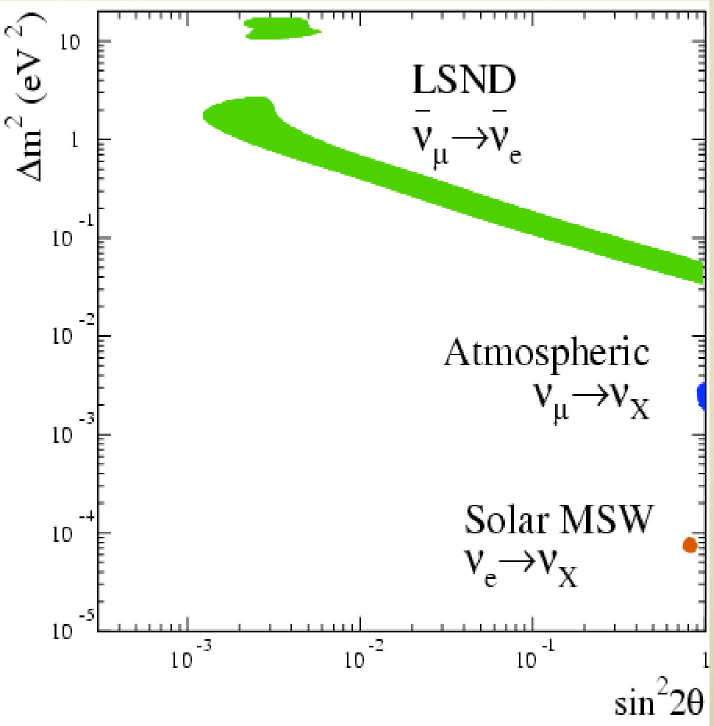
- The LSND experiment observed a small excess of $\overline{\nu}_e$ evens in a $\overline{\nu}_\mu$ beam

  Data excess: 87.9 ± 22.4 ± 6.0 (3.8 σ)

  Best fit: $\Delta m^2 \sim 1$ eV^2, $\sin^2 2\theta \sim 0.003$

  hep-ex/01014049





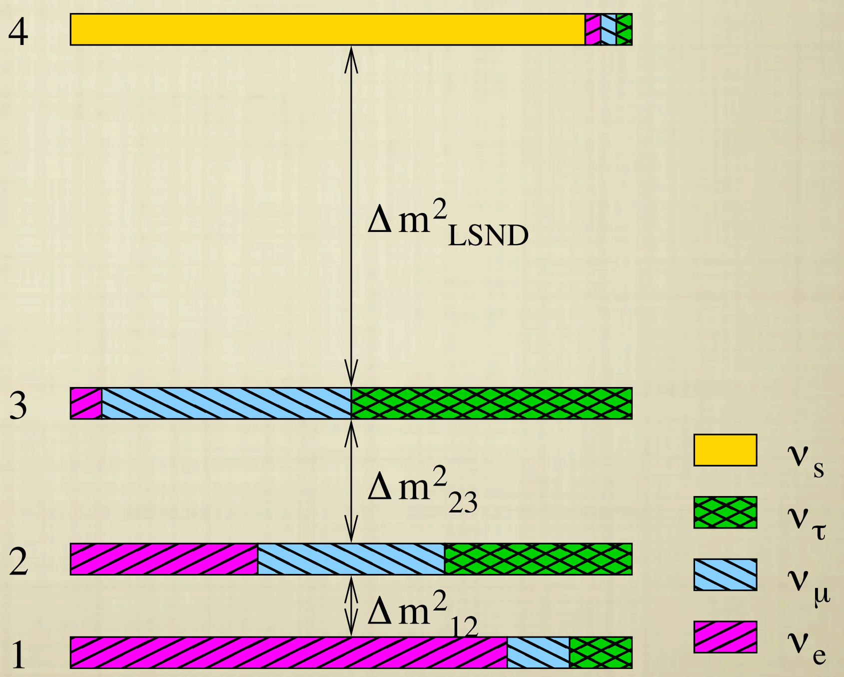
Active-sterile Neutrino Oscillation?

- A possible explanation of the LSND signal:
  - Oscillation with active and “sterile” neutrinos

A simple realization of the sterile neutrino is right-handed neutrino ν_R, which can be mixed with active ν_L.

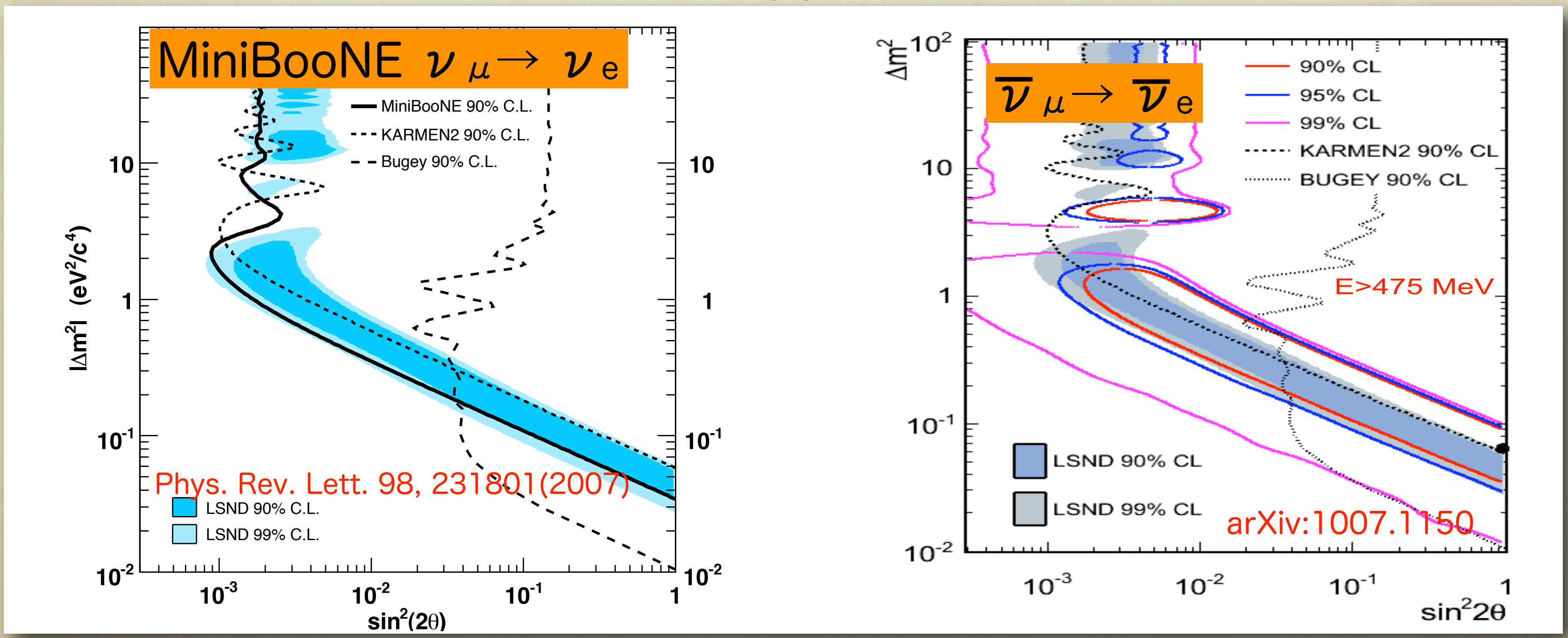
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \cdots \end{pmatrix}$$

3+1 sterile neutrino scheme



MiniBooNE
ν_e Appearance Results

- MiniBooNE experiment recently tested the LSND signal.
- Ruled out most of LSND region in $\nu_\mu \to \nu_e$ search.
- However, observed a data excess in $\bar{\nu}_\mu \to \bar{\nu}_e$ measurement.
  - Consistent with LSND???
- We want to test this with disappearance measurements!



Appearance vs. Disappearance

How can we test appearance signals by disappearance measurements?

$\nu_\mu \to \nu_e$ appearance

$$P(\nu_\mu \to \nu_e) = 4\boxed{|U_{e4}|^2}\boxed{|U_{\mu 4}|^2}\sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

ν_e disappearance

$$P(\nu_e \to \nu_x) = 1 - 4\boxed{|U_{e4}|^2(1-|U_{e4}|^2)}\sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

ν_μ disappearance

$$P(\nu_\mu \to \nu_x) = 1 - 4\boxed{|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)}\sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

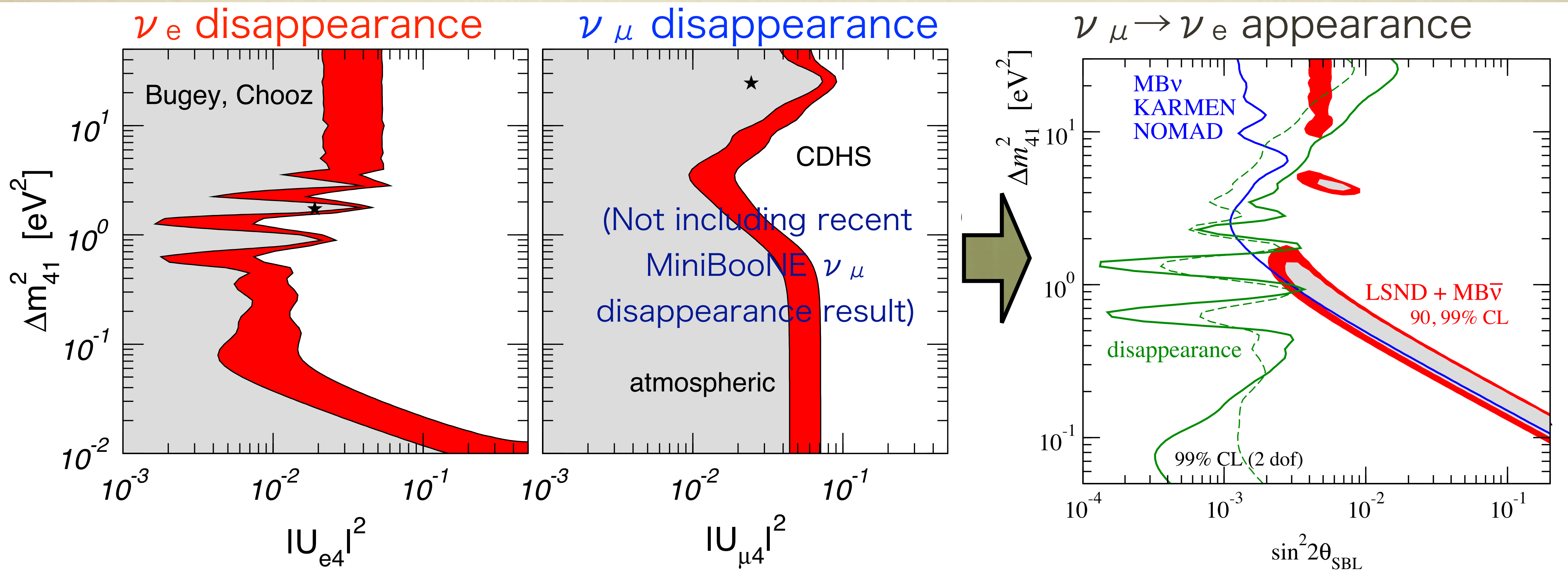
$\nu_\mu \to \nu_e$ appearance probability can be constrained by ν_e and ν_μ disappearance measurements!

Impact of Disappearance Experiments

Compatibility of the existing measurements in (3+1) model

M. Maltoni, J. Conf. Ser. 110, 082011 (2008)

J. Kopp, M. Maltoni, T. Schwetz, arXiv:1103.4570

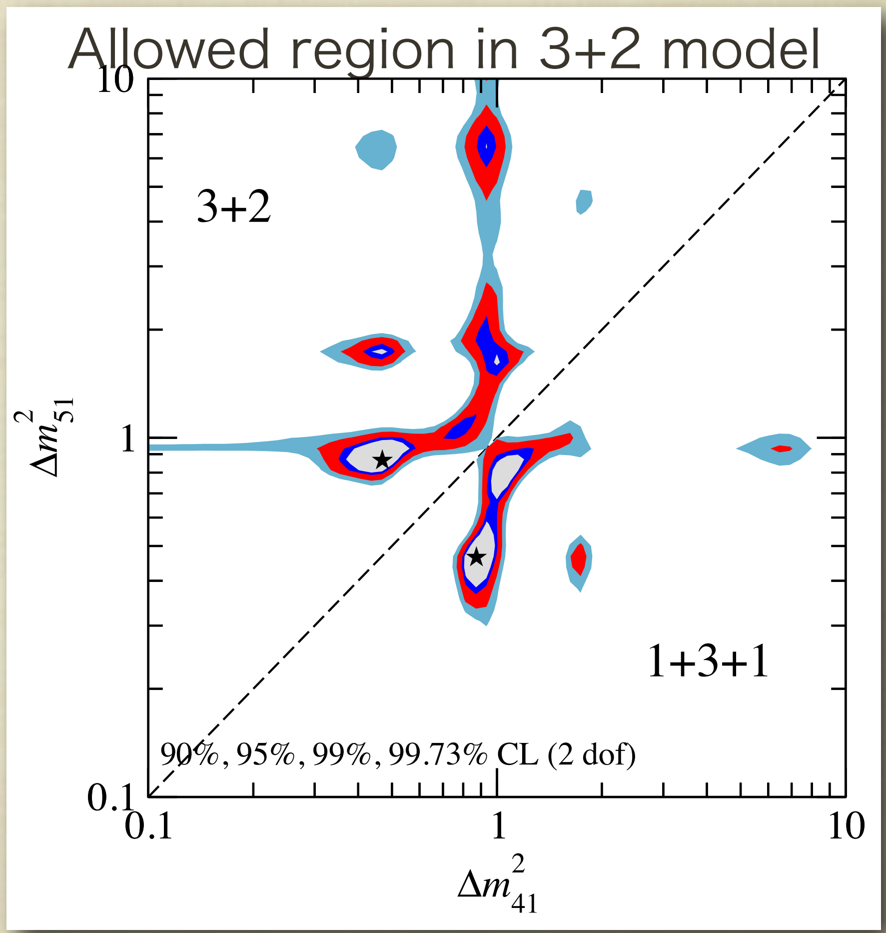


- LSND allowed region is incompatible with disappearance results.
- Disappearance measurement is a powerful tool!

Other Scenarios

- 3+2 sterile neutrino mixing
  - PRD 76, 093005 (2007)
  - PRD 80, 073001 (2009)
  - arXiv:1103,4570
- Sterile neutrinos in extra dimensions
  - PRD 72, 095017 (2005)
- Decaying sterile neutrino
  - JHEP 09, 048 (2005)
- CPT violation
  - PRD 77, 033001 (2008)

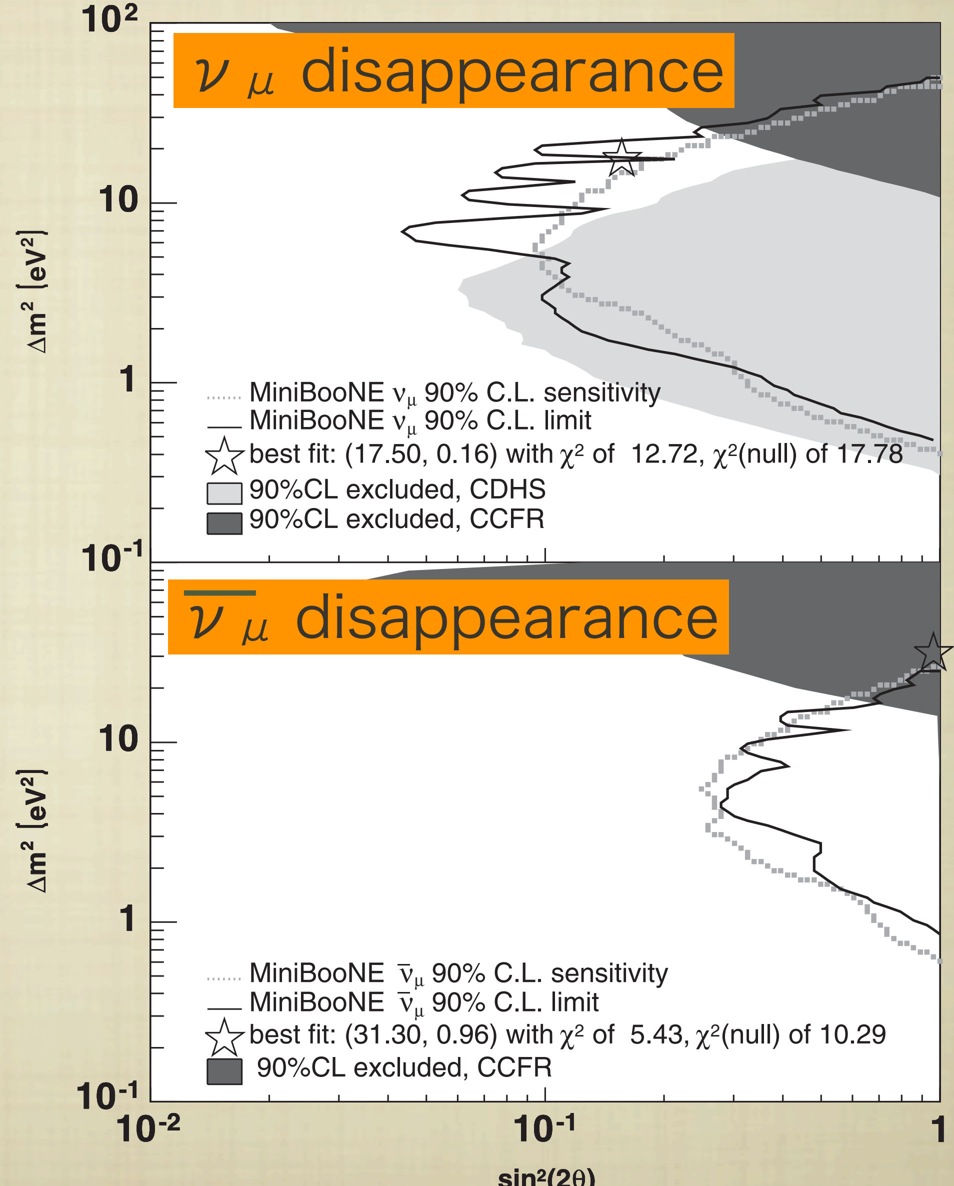
J. Kopp, M. Maltoni, T. Schwetz, arXiv:1103.4570



Disappearance measurements can constrain these models.

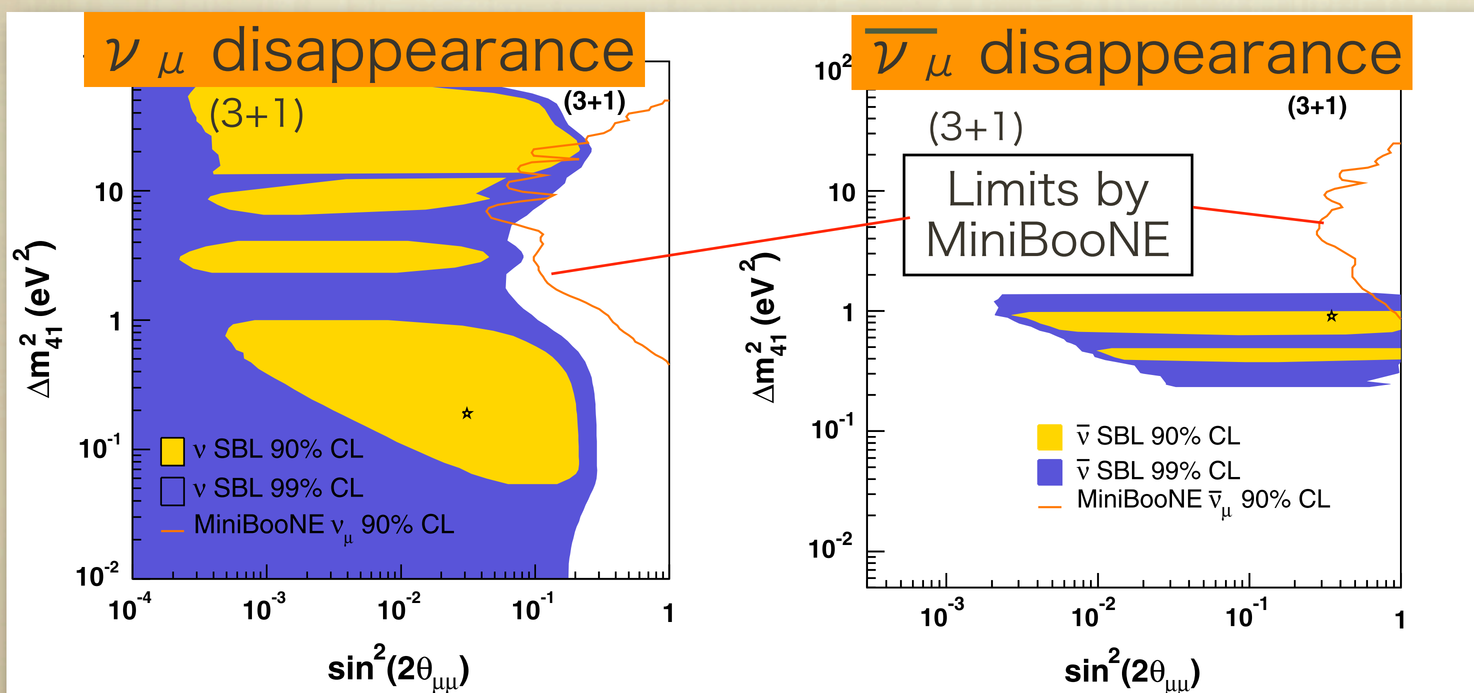
ν_μ Disappearance Measurements

- Important to test ν_μ and $\bar{\nu}_\mu$ disappearance independently.
  - Testing CPT-invariance.
- Recently, MiniBooNE searched for ν_μ and $\bar{\nu}_\mu$ disappearance with MiniBooNE data only (PRL 103, 061802)
- This analysis used the flux shape only, and suffered from large flux and cross section uncertainties.



ν_μ Disappearance Measurements (cont'd)

- Large allowed region from a global fit to world existing data with the (3+1) model, if we fit ν_μ and $\overline{\nu}_\mu$ independently.
- Why don't you improve MiniBooNE results **with a near detector (SciBooNE).**
  - **Flux+shape analysis with reduced systematic error.**

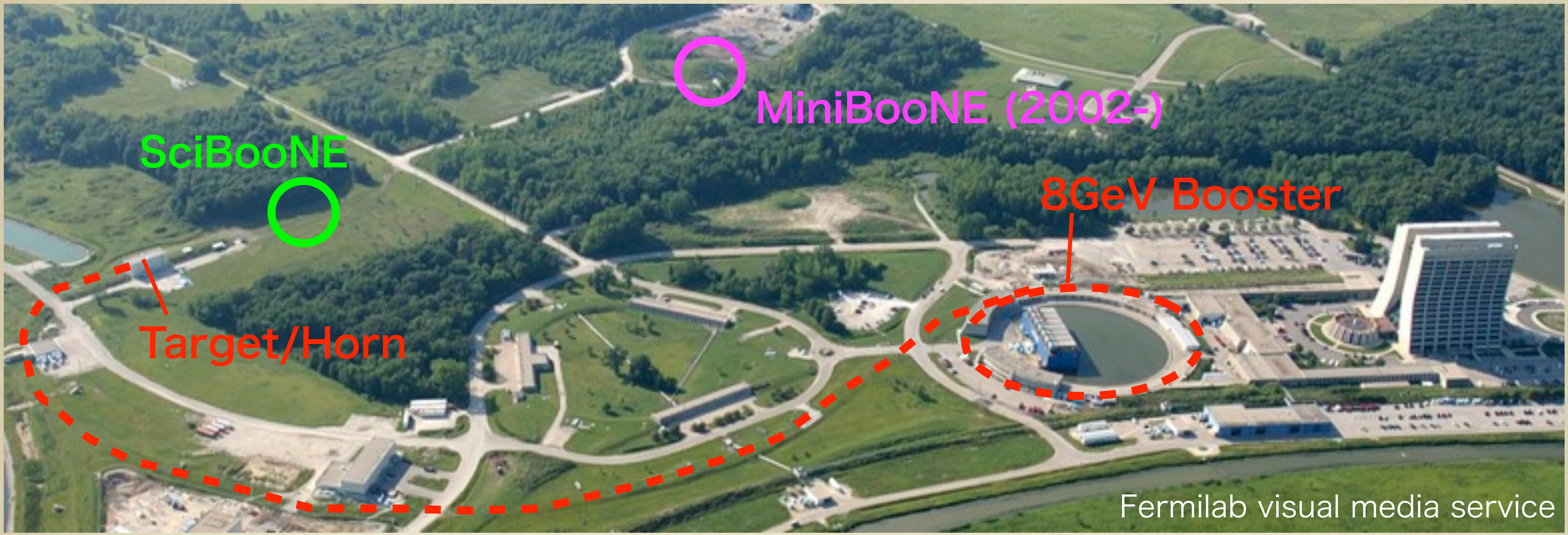


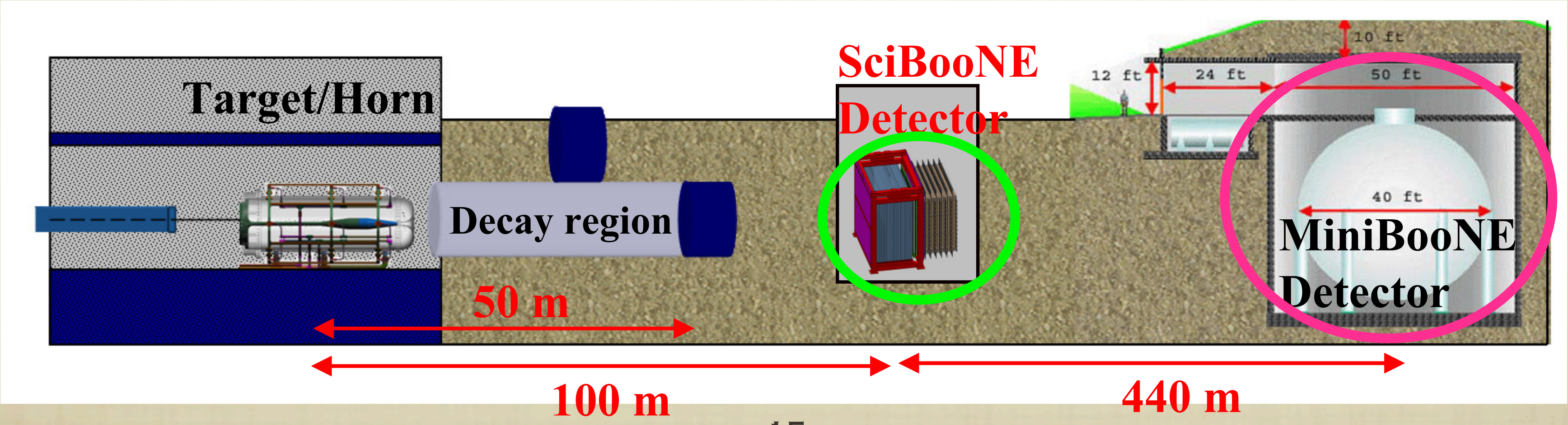
Allowed regions from (3+1) global fits

G. Karagiorgi, et al. Phys. Rev. D **80**, 073001 (2009)

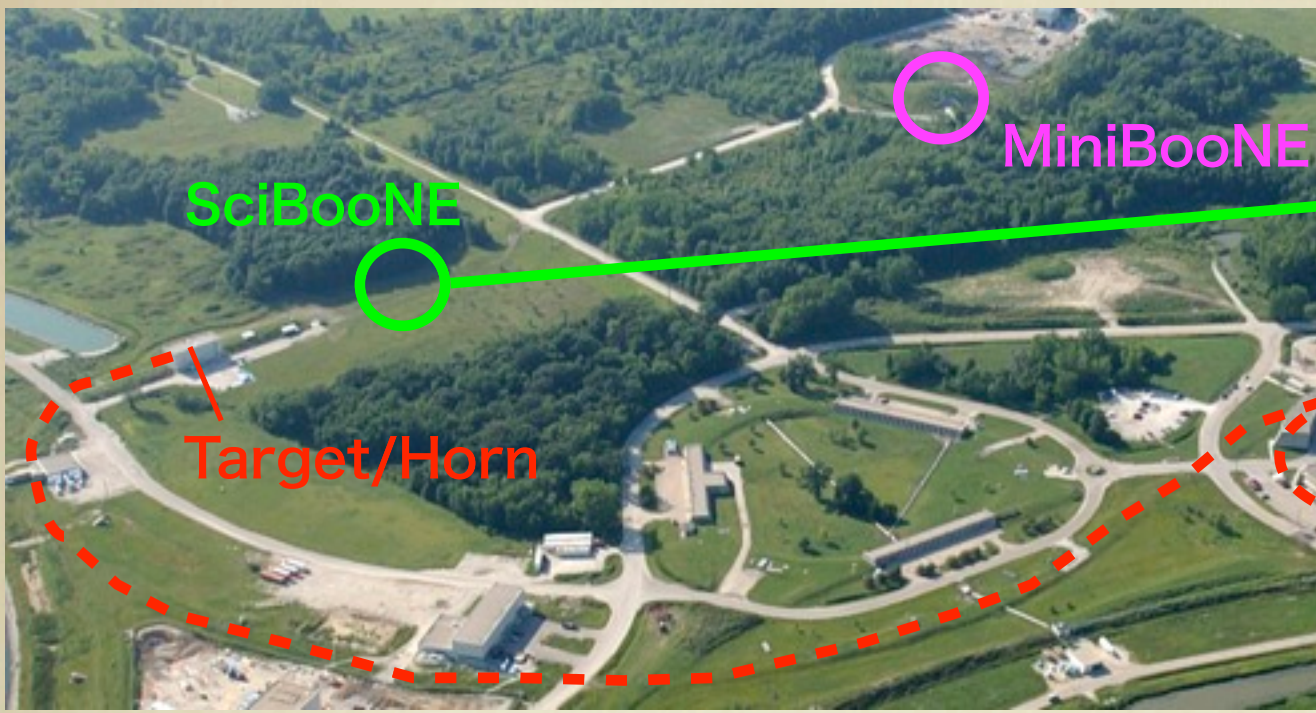
Experiments

Overview

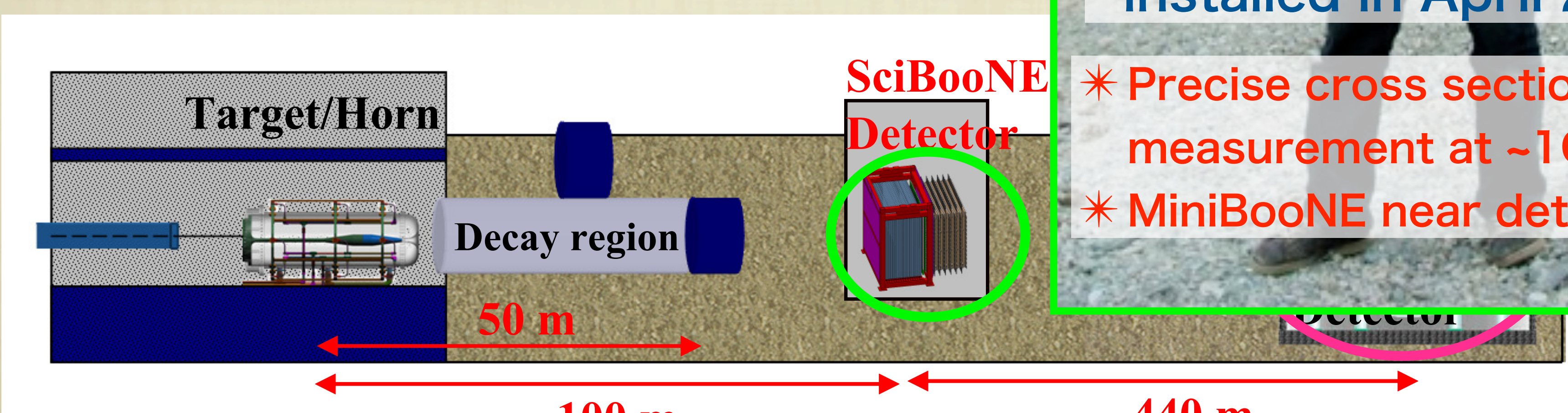

MiniBooNE (2002-)
SciBooNE
8GeV Booster
Target/Horn
Fermilab visual media service


Target/Horn
Decay region
SciBooNE
Detector
12 ft
24 ft
50 ft
10 ft
40 ft
MiniBooNE
Detector
50 m
100 m
440 m

Overview


MiniBooNE
SciBooNE
Target/Horn


SciBooNE detector
installed in April 2007
✳ Precise cross section measurement at ~1GeV
✳ MiniBooNE near detector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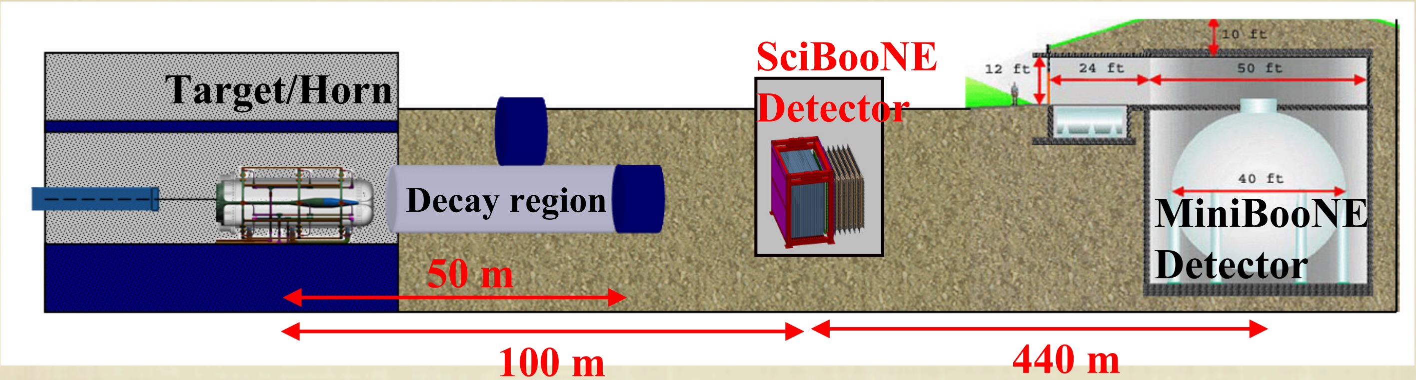
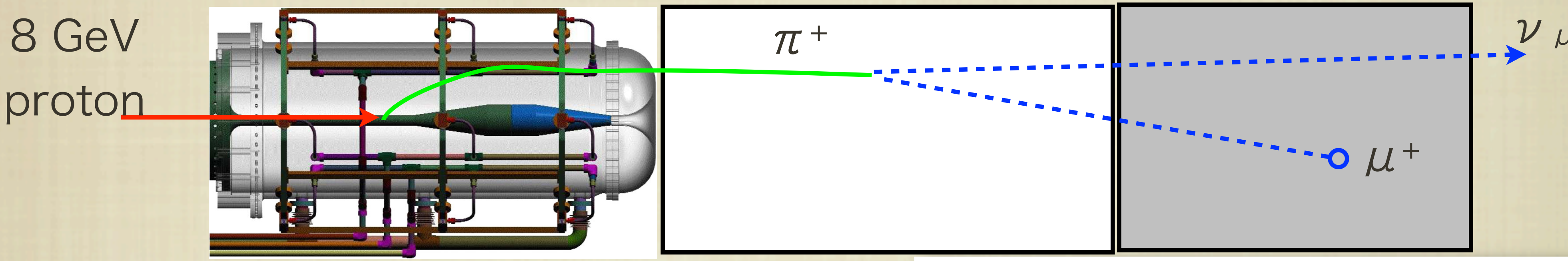
Overview

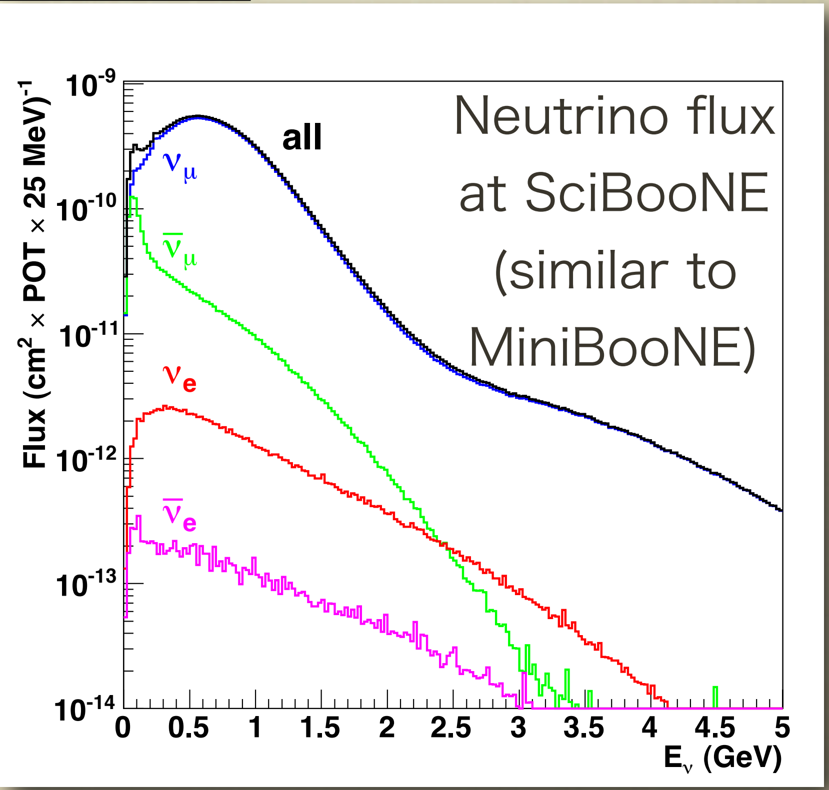


- MiniBooNE experiment (2002 -) is designed to test the LSND signal at L/E ~ 0.7 meter/MeV
  - L/E for MiniBooNE: 540m / 0.8 GeV ~ 0.7 m/MeV
- SciBooNE experiment (2007-2008) has two purposes
  - Precise measurement of neutrino cross section for future oscillation experiments (T2K, etc)
  - MiniBooNE near detector

Common beamline + Common neutrino target (both carbon) → Significant reduction of systematic errors

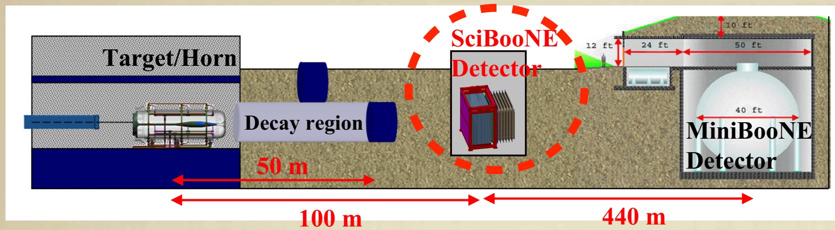
Fermilab Booster Neutrino Beam



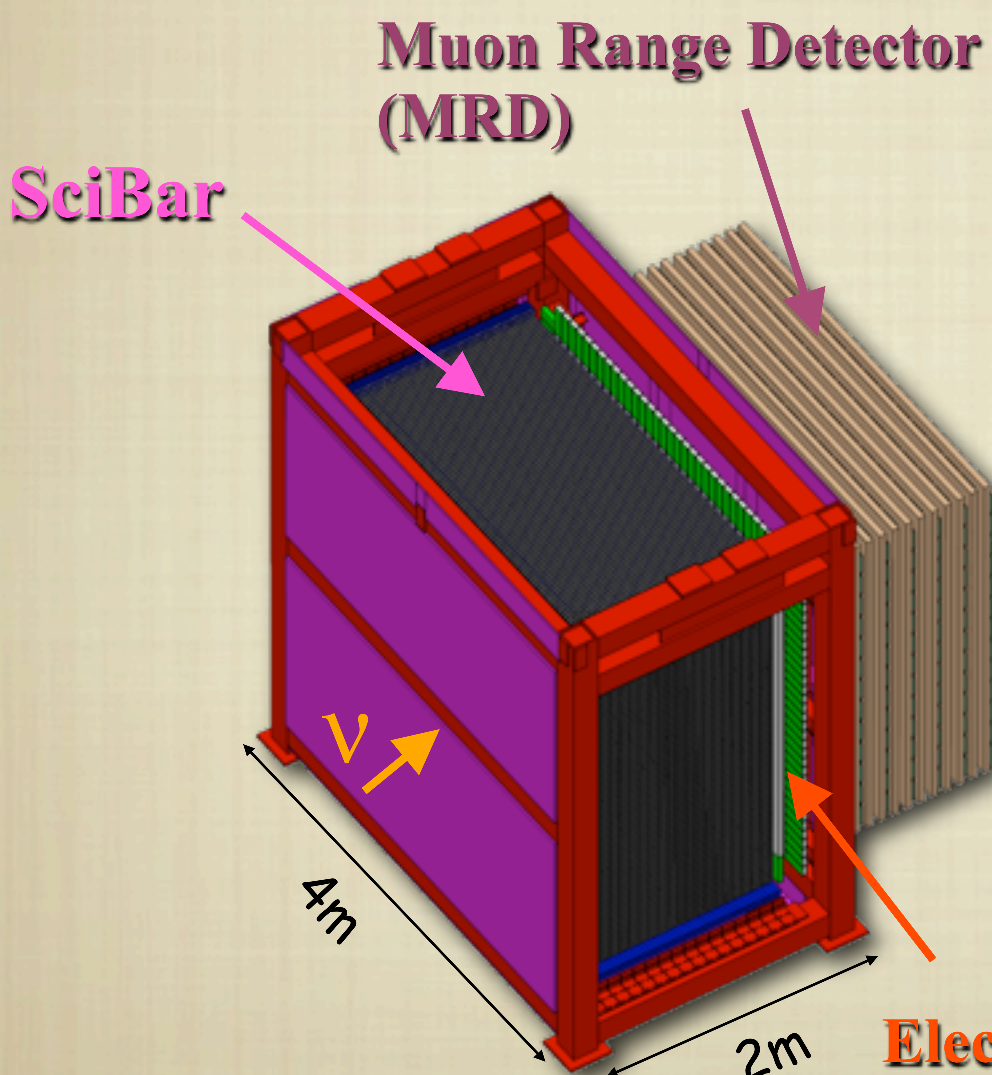


- Intense ν_μ beam with the mean energy of ~0.8 GeV
  - 93% pure ν_μ beam.
- Anti-ν_μ beam is also produced by inverting horn polarity.

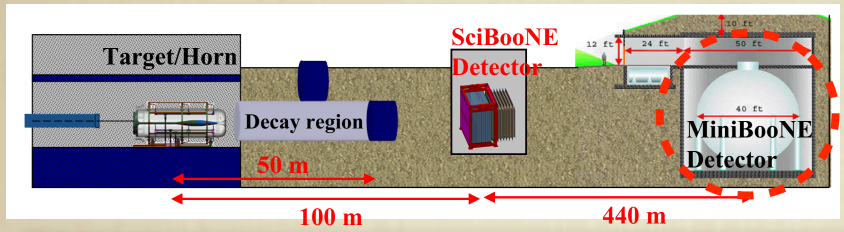
SciBooNE detector

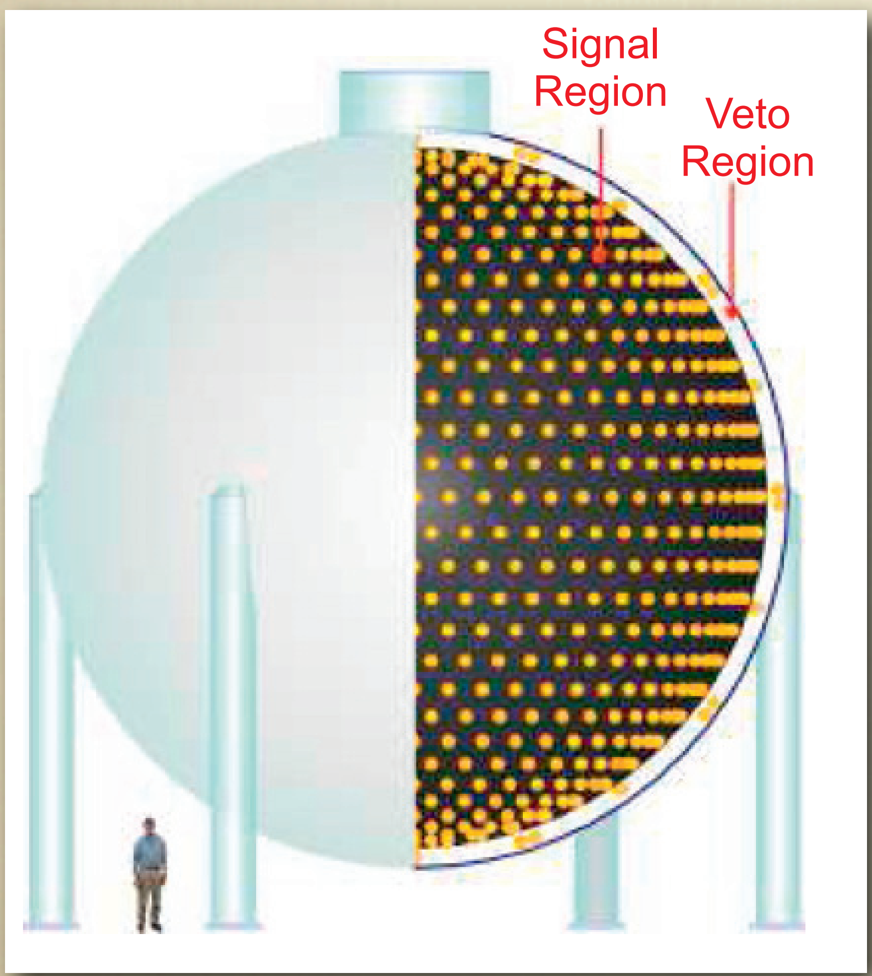


- Located at 100 m from target.
- SciBar:
  - Fully active scintillator tracker (~14000 strips)
  - Neutrino target (~10 ton)
  - Main component： CH
- Muon Range Detector (MRD)
  - A sandwich type detector of steel + plastic scintillator.
  - Reconstruct muon momentum from its path-length



MiniBooNE detector



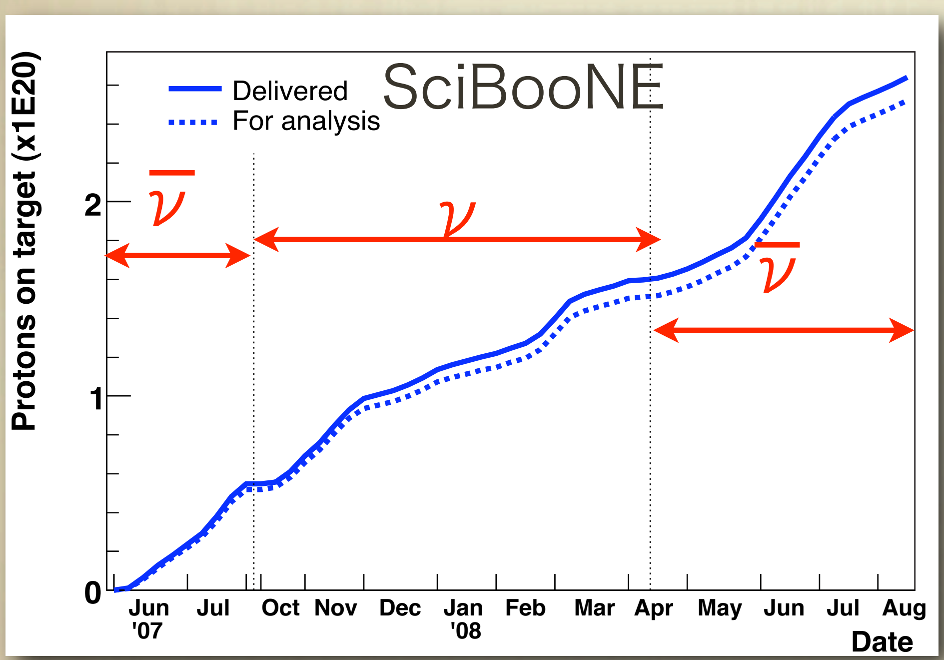


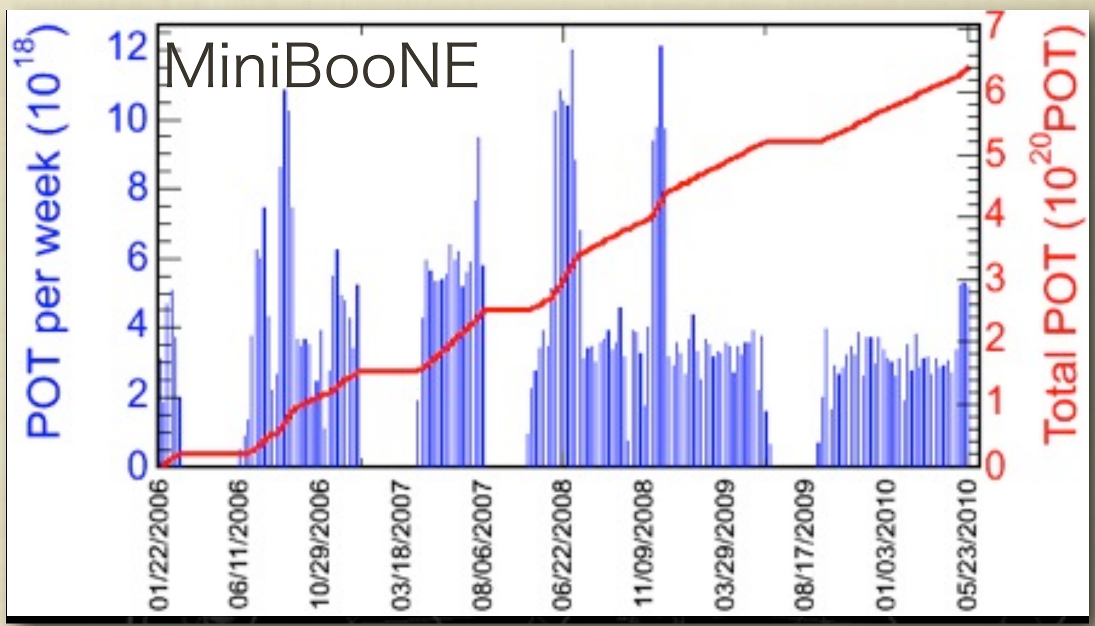
- Located at 540 m from target
- Mineral oil Cherenkov detector
  - n = 1.47
  - Select ν_μ by single muon and its decay-electron signal.
  - Total mass: ~800 ton
  - Main component: CH_2
- Taking beam data since 2002

2 detectors share the beam and the target material (both carbon)

Data sets

Period	BNB Mode	SciBooNE POT	MiniBooNE POT
Sep. 2002 - Dec. 2005	Neutrino	–	5.58×10^{20}
Jan. 2006 - Aug. 2007	Antineutrino	0.52×10^{20} (from Jun. 2007)	1.71×10^{20}
Oct. 2007 - Apr. 2008	Neutrino	0.99×10^{20}	0.83×10^{20}
Apr. 2008 - present	Antineutrino	1.01×10^{20} (until Aug. 2008)	ongoing





Analysis of the full neutrino data sets is presented

- SciBooNE: 0.99×10^{20} POT
- MiniBooNE: $(5.58 + 0.83) \times 10^{20}$ POT

Analysis

Analysis Overview

Two independent analyses

Spectrum fit

SciBooNE data

↓ Spectrum fit

CC interaction rate measurement

↓

MiniBooNE rec. E_ν prediction

↕ Oscillation Fit

MiniBooNE rec. E_ν data

Advantage:
Decouple oscillation fit from constraint.
Observe the amount of constraint.

Simultaneous fit

SB + MB Rec. E_ν Data

↕ Oscillation Fit

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Advantage:
Direct fit for disappearance in SciBooNE and MiniBooNE.
Correlation between the two constrain systematic error.

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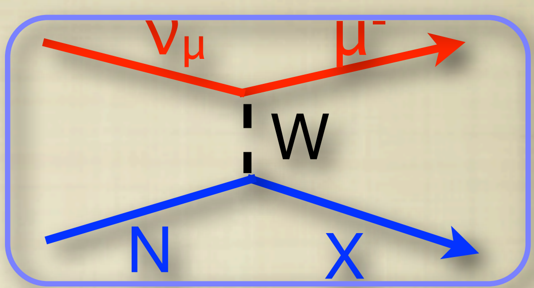
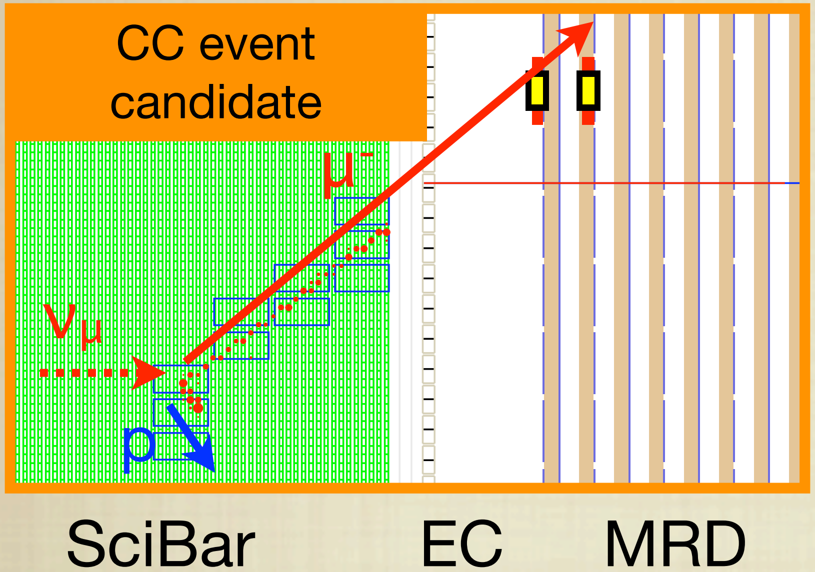
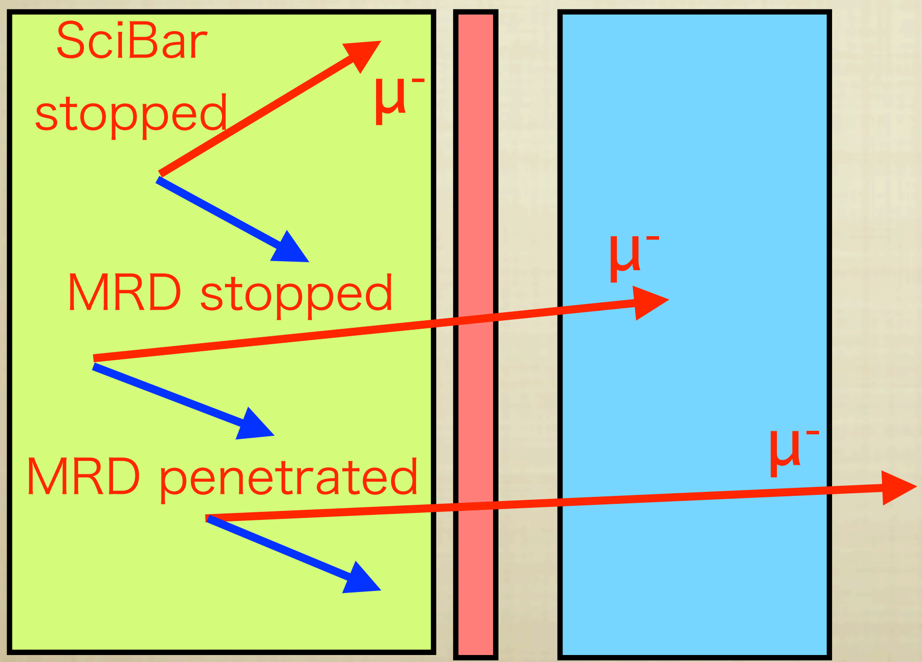
SciBooNE event selection



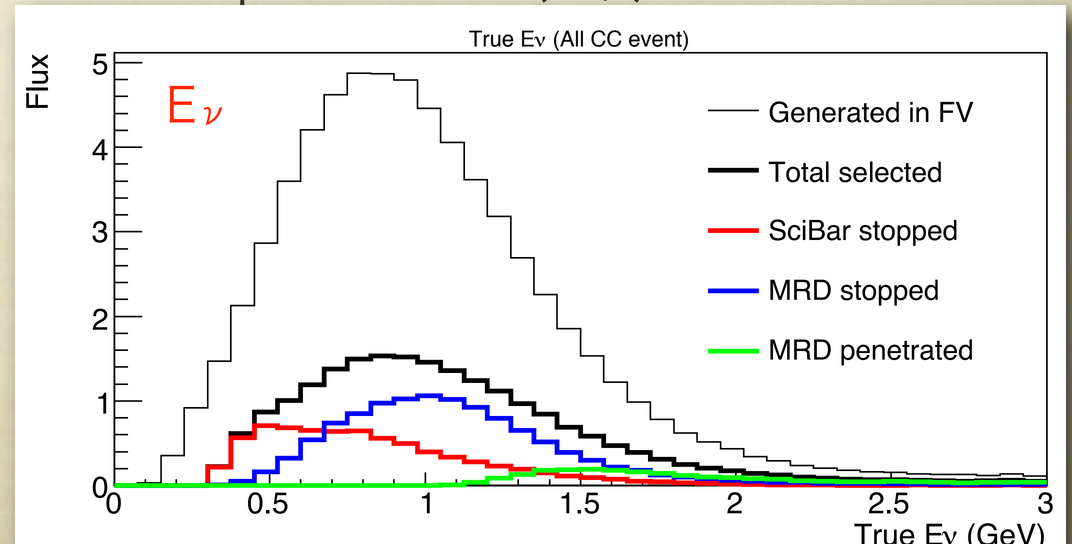




Use charged current inclusive sample

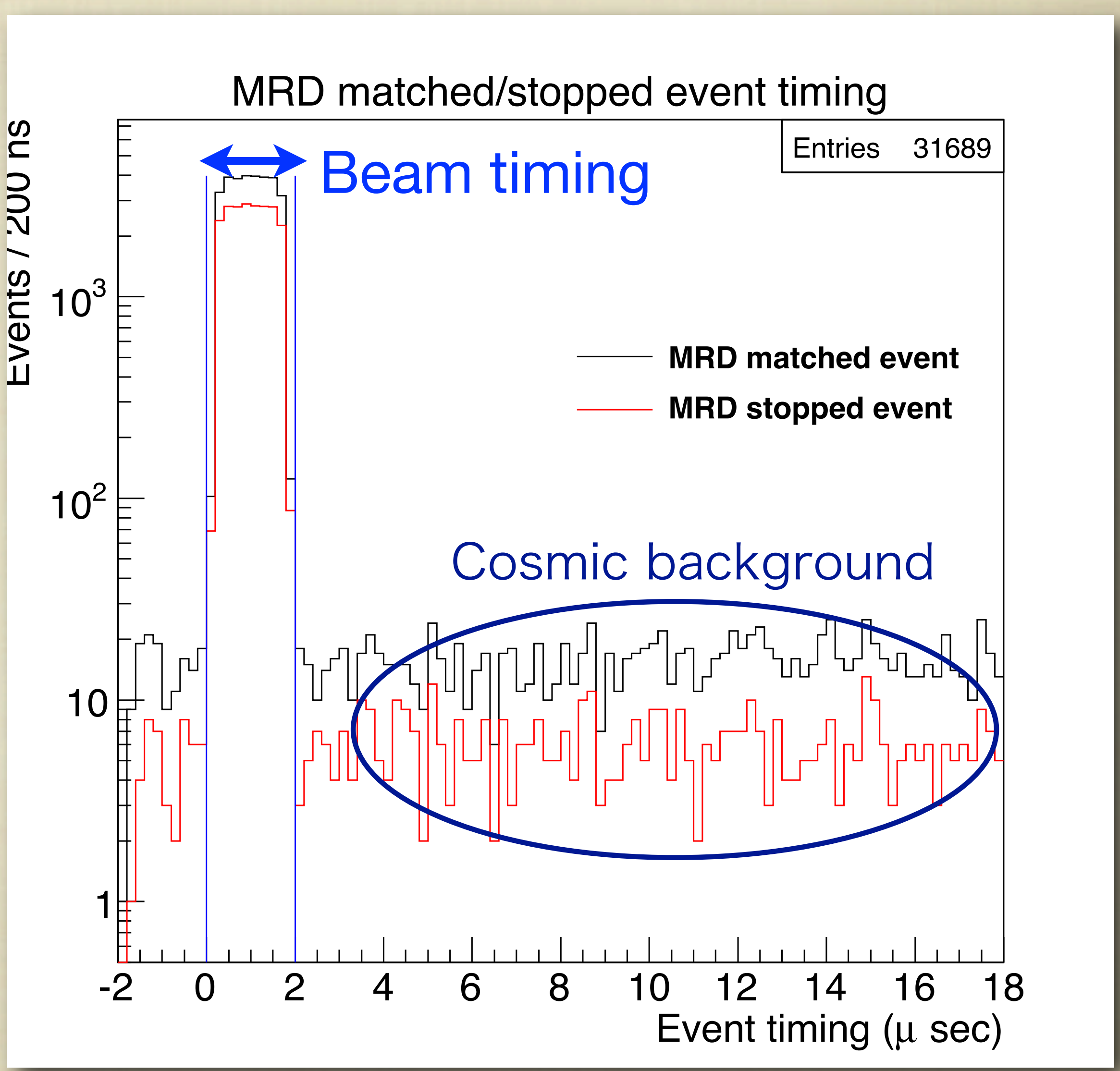
- Select MIP-like energetic tracks (P_μ>0.25GeV)
- Reject side-escaping muons.
- 3 samples:
  - SciBar-stopped (P_μ, θ_μ)
  - MRD-stopped (P_μ, θ_μ)
  - MRD-penetrated (θ_μ)

P_μ: Muon momentum reconstructed by its path-length
θ_μ: Muon angle w.r.t. beam axis



Neutrino event selection

- Booster provide pulsed beam with 1.6 μsec width.
- Require the event timing to be within the 2 μsec beam timing window.
  - Less than 0.5% cosmic ray contamination.
- ~14K SciBar-stopped events.
- ~20K MRD-stopped events.
- ~4K MRD-penetrated events.



Muon distributions

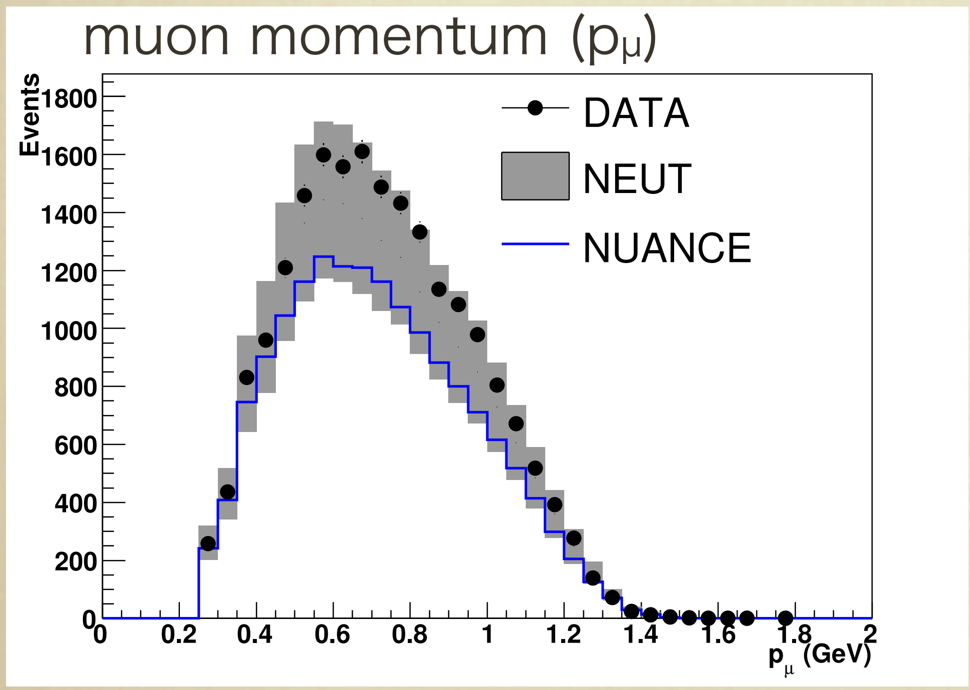
- 2 neutrino interaction simulators are used:

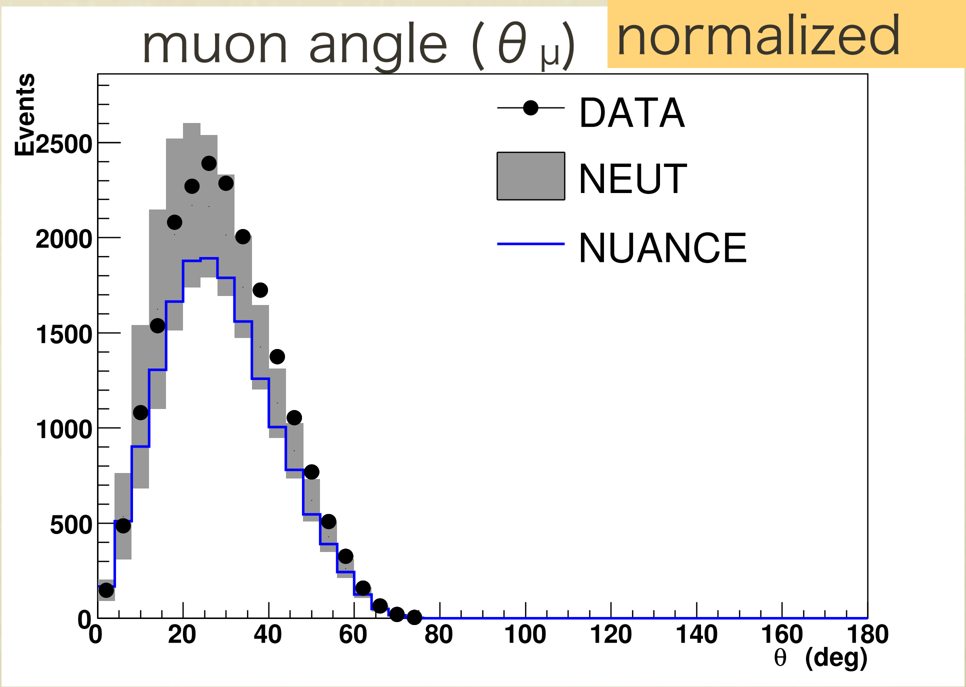
NEUT: SK, K2K, T2K, etc (+ all other cross section measurements in SciBooNE)
NUANCE: MiniBooNE, etc (Use NUANCE for this joint oscillation analysis)

Both tuned to explain data, but predict different cross sections.

Testing these in a single experiment (SciBooNE) is another important topic!

MRD-stopped
Absolutely
normalized

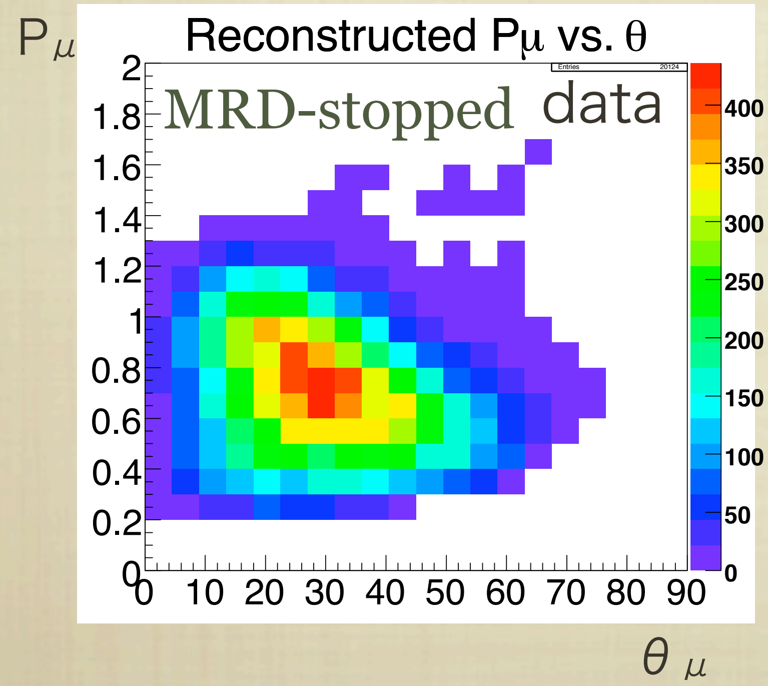


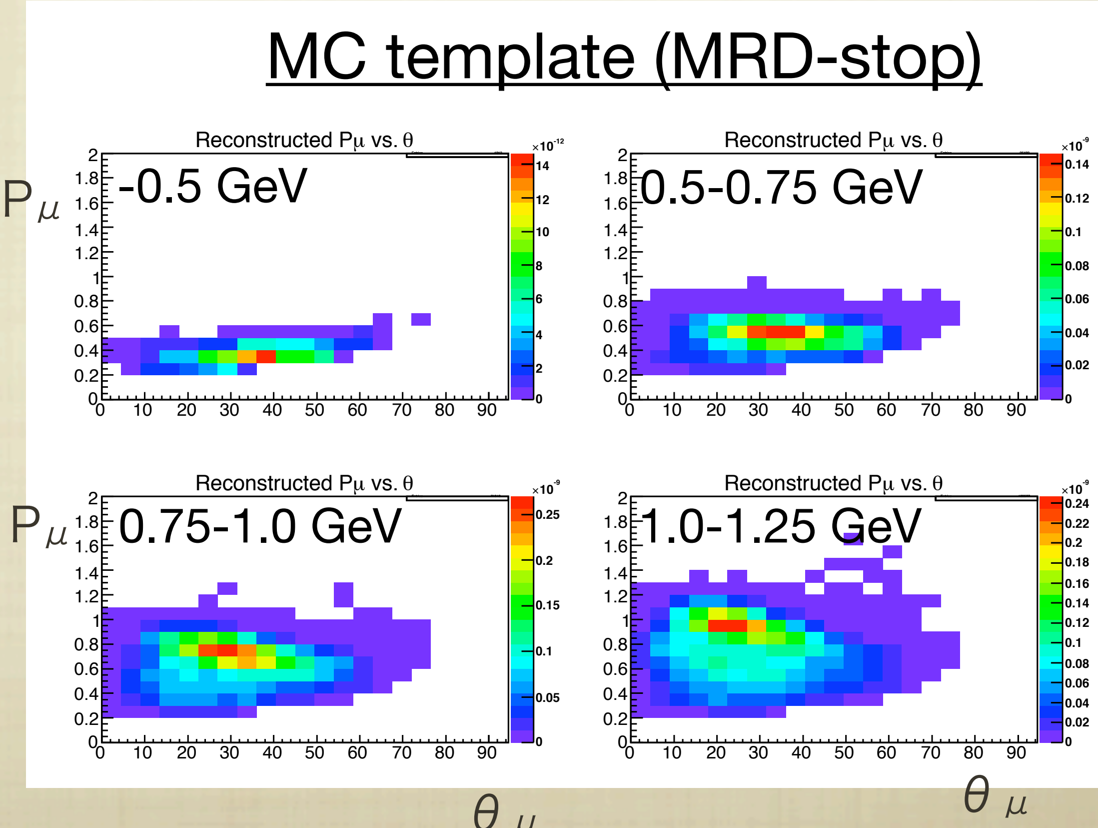


MC reproduce data within the systematic error

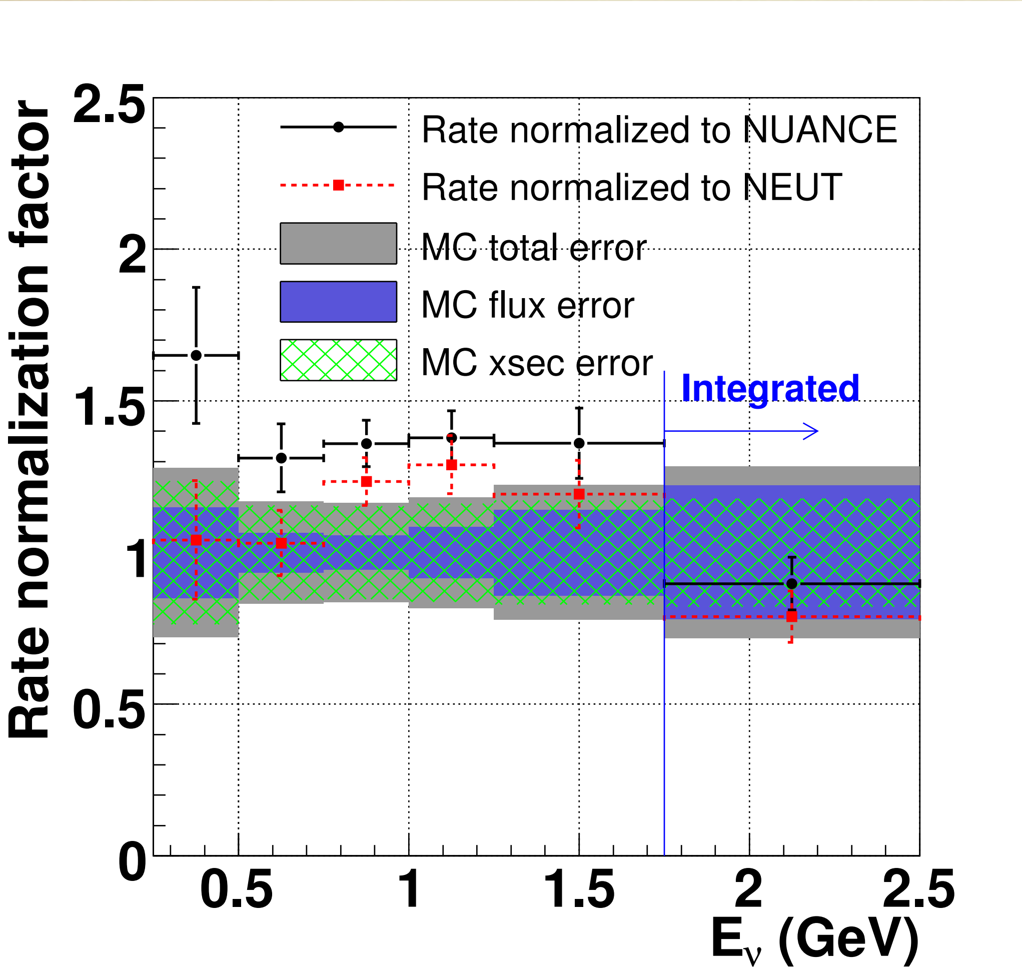
Spectrum fit

- Tune MC prediction by re-weighting as a function of true neutrino energy.
- Determine the rate normalization factor which best fits to p_μ vs. θ_μ 2D distributions.
  - All three samples (SciBar-stop, MRD-stop and MRD-penetrated samples) are used simultaneously.





CC interaction rate



- Extract CC interaction rate

$$\boxed{\mathcal{R}_i = \frac{f_i \cdot \mathcal{N}_i^{pred} \cdot P_i}{\epsilon_i}}$$

normalization factor

# of event prediction

Purity

Efficiency

- This is product of (flux) x (cross-section)

Direct input for this joint ν_μ disappearance analysis

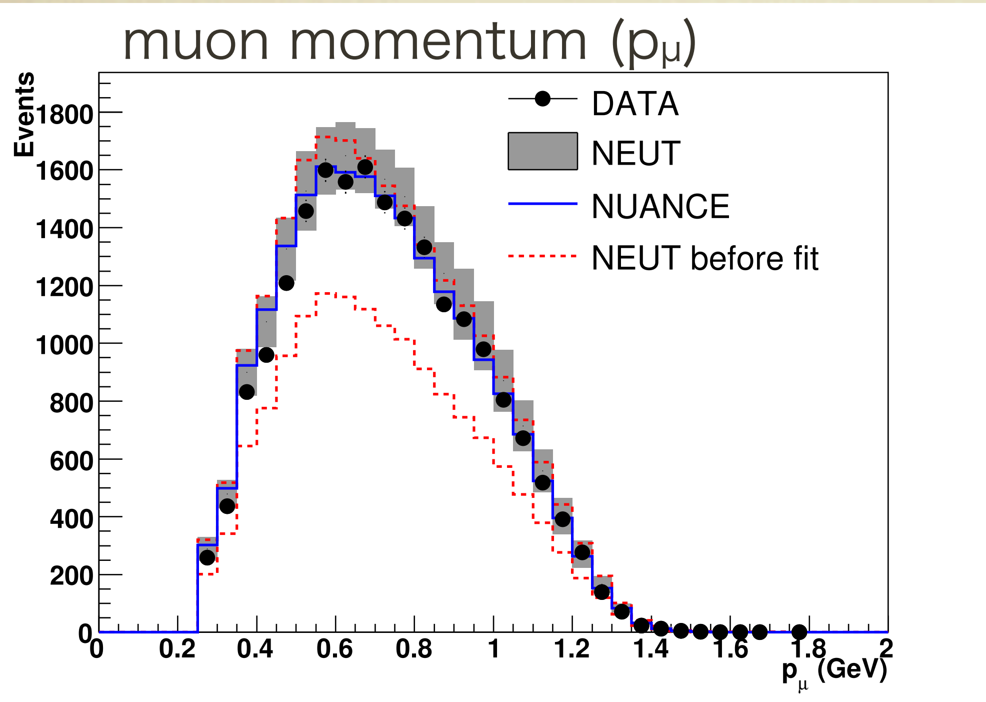
Published in Phys. Rev. D **83**, 012005 (2011)

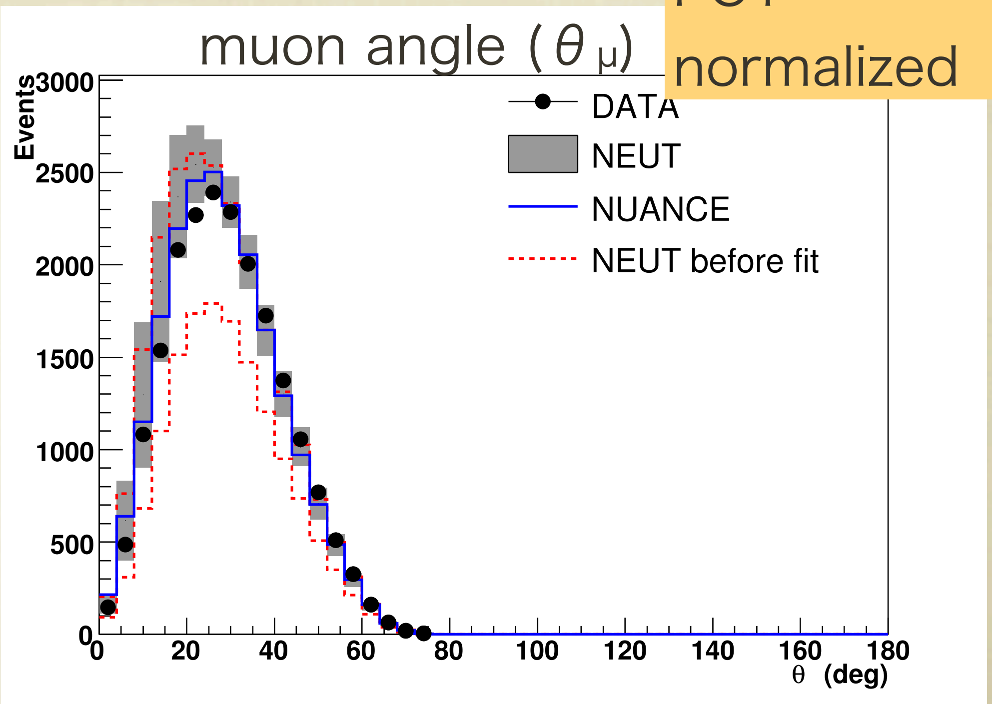
Parameter	f_0	f_1	f_2	f_3	f_4	f_5
E_ν range (GeV)	0.25 - 0.5	0.5 - 0.75	0.75 - 1.0	1.0 - 1.25	1.25 - 1.75	1.75+

Distributions after fit

- Apply obtained rate normalization factors.
- Confirmed that the distribution well reproduce the data, and the errors become much smaller.

MRD-stopped
POT
normalized





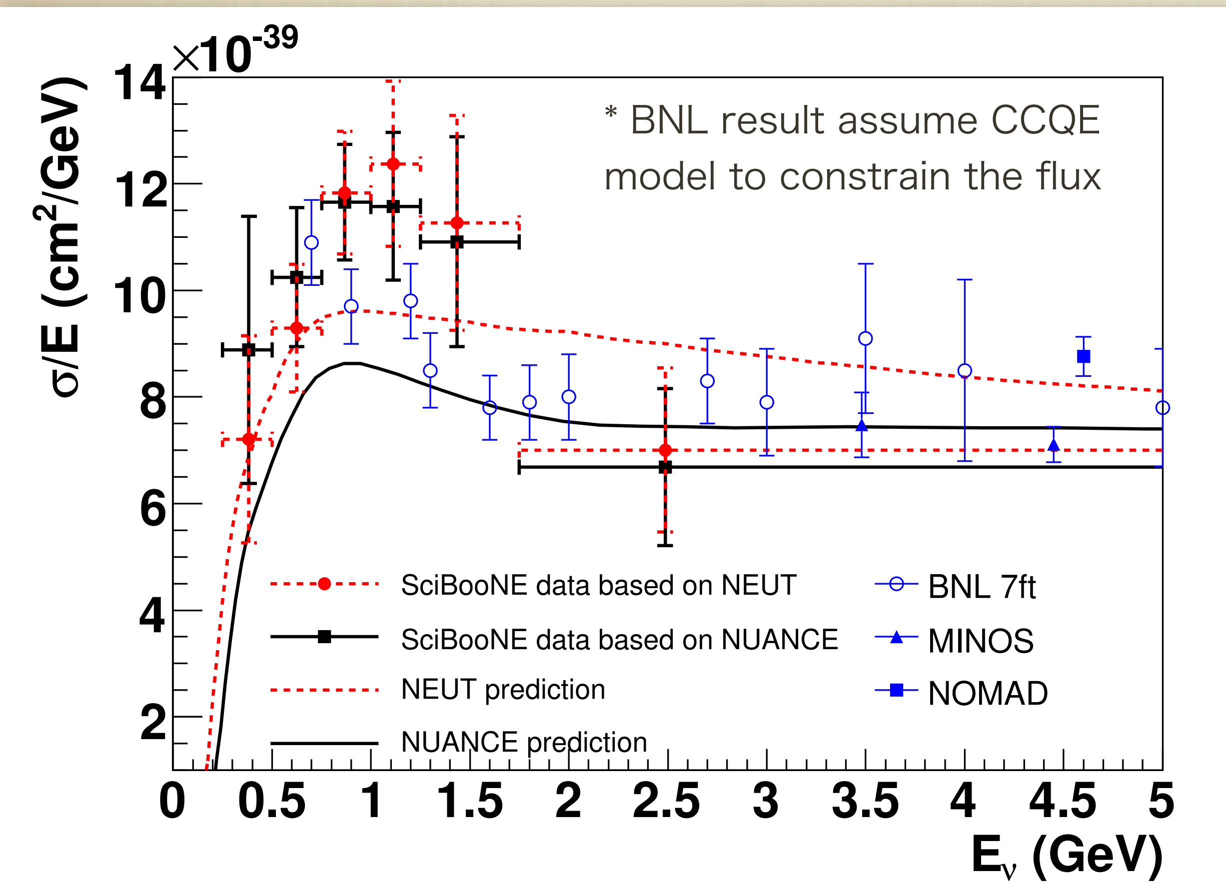
CC inclusive cross section

Extract CC inclusive cross section:

$$\boxed{\sigma_i = f_i \cdot < \sigma_{CC}^{pred} >_i = \frac{f_i \cdot N_i^{pred} \cdot P_i}{\epsilon_i \cdot T \cdot \Phi_i}},$$

T: number of target nucleon

Φ: total flux



- First measurement of CC-inclusive cross section on carbon in the 1 GeV region
- NEUT and NUANCE based cross-section are consistent.
- Covers up to ~ 3 GeV.
- Consistent with MINOS, NOMAD and old BNL bubble chamber (deuterium) measurements

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Observe the amount of constraint.

Simultaneous fit

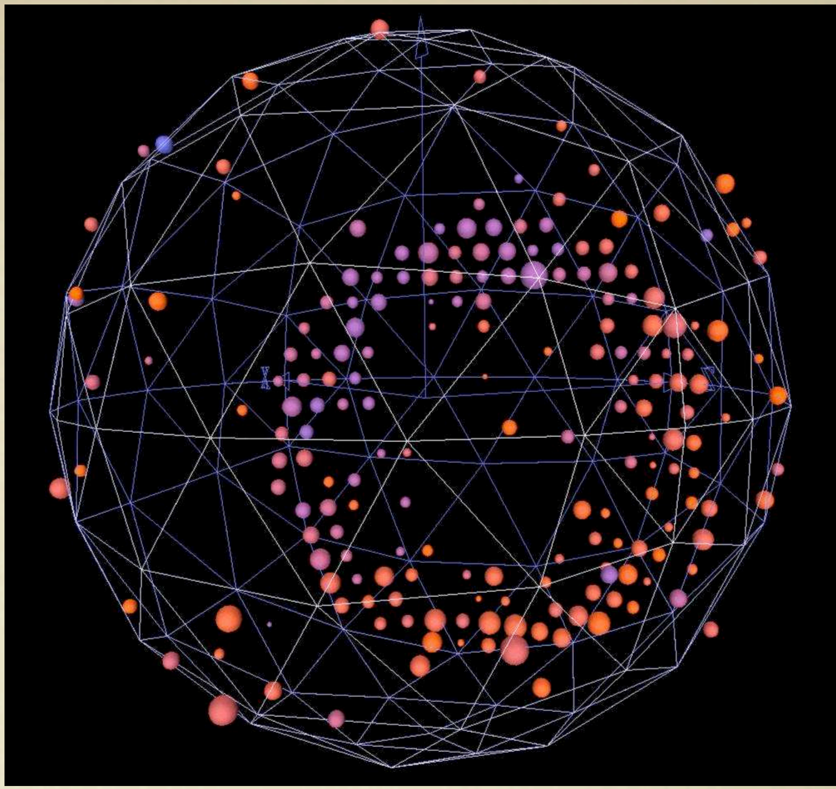
SB + MB Rec. E_ν Data

↕ Oscillation Fit

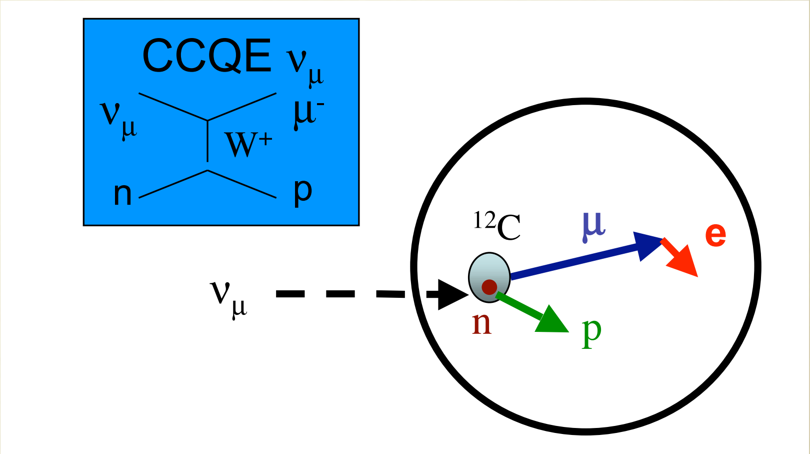
SB + MB Rec. E_ν Prediction

Advantage:
Direct fit for disappearance in SciBooNE and MiniBooNE.
Correlation between the two constrain systematic error.

MiniBooNE reconstruction



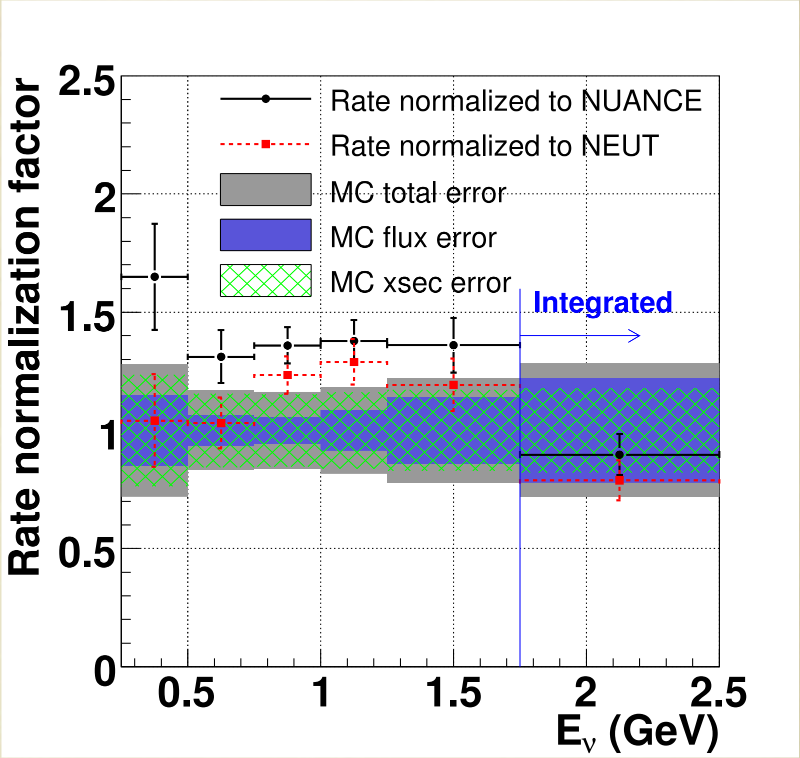
- Employ same selection/reconstruction as used in previous MiniBooNE-only analysis (PRL **103**, 061802(2009))
- Select CC quasi-elastic (QE) (νn→μp) like events by requiring hits from muon and its decay electron.
- Reconstruct muon kinematics from the Cherenkov light yield.
- Reconstruct neutrino energy from muon kinematics, assuming CC-QE interaction.



$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_B)^2 - m_\mu^2 + 2(m_n - E_B)E_\mu}{2(m_n - E_B - E_\mu + p_\mu \cos\theta_\mu)}$$

MiniBooNE prediction

- Apply the rate normalization factor obtained by SciBooNE analysis to MiniBooNE.

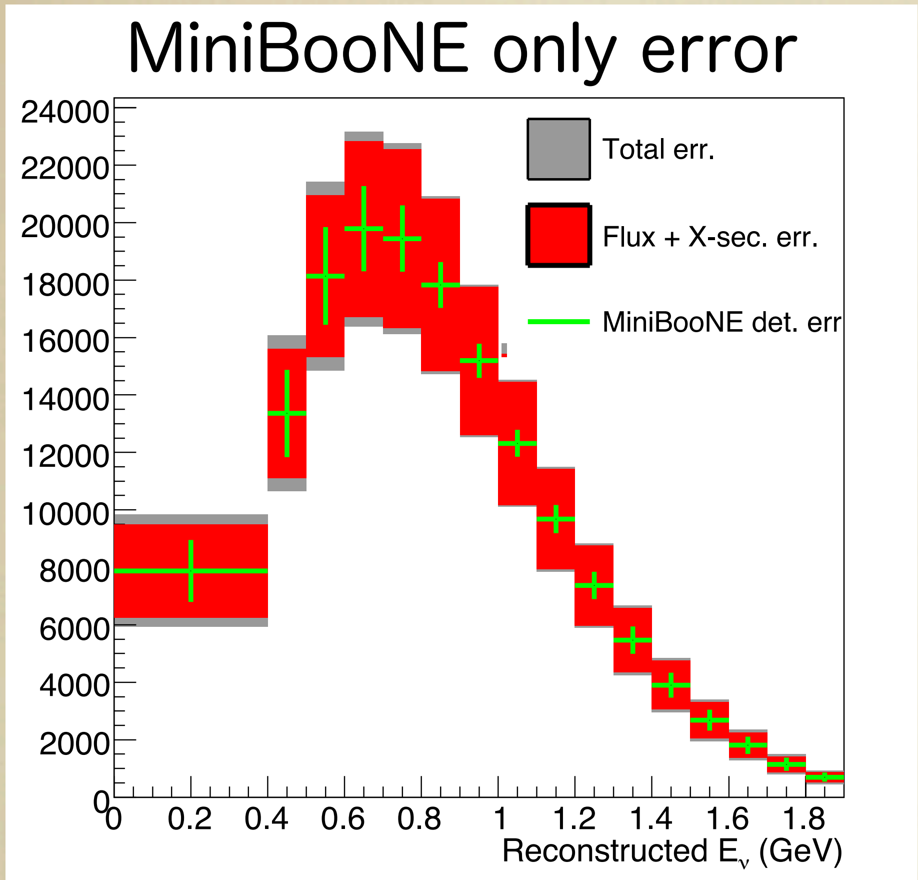


Systematic errors:

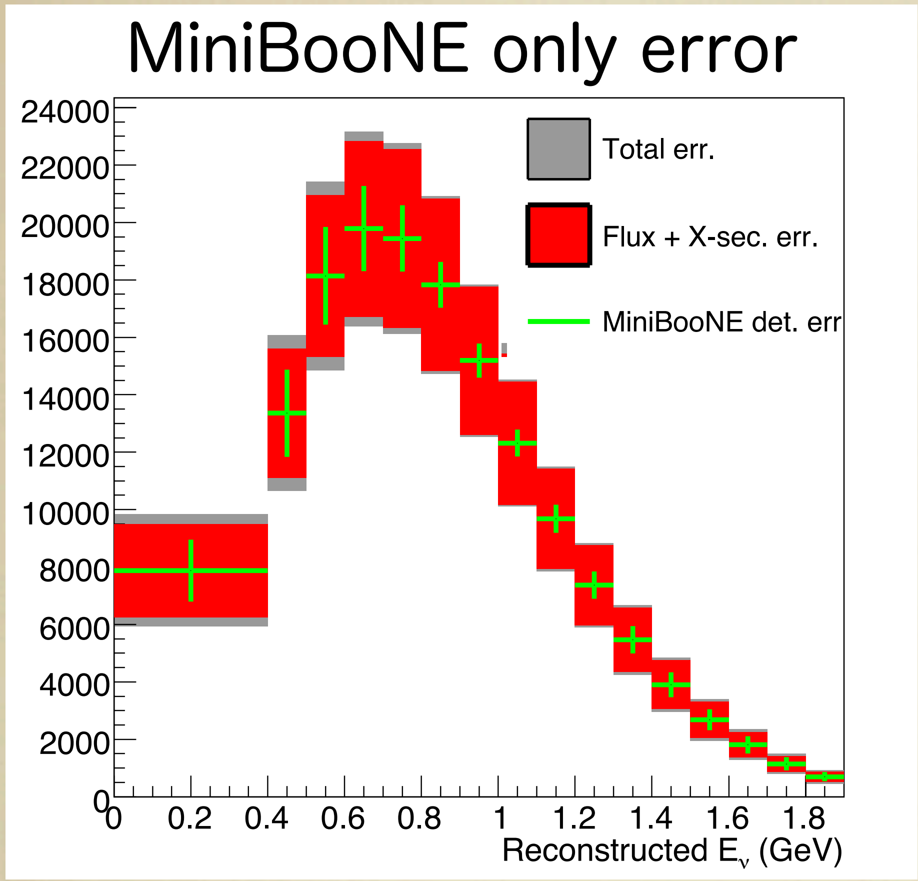
- Most of flux and cross section errors cancel by taking ratio between SciBooNE and MiniBooNE.
- Remaining errors:
  - Relative flux difference
  - Efficiency variation due to cross section model uncertainties.
  - MiniBooNE detector response errors.

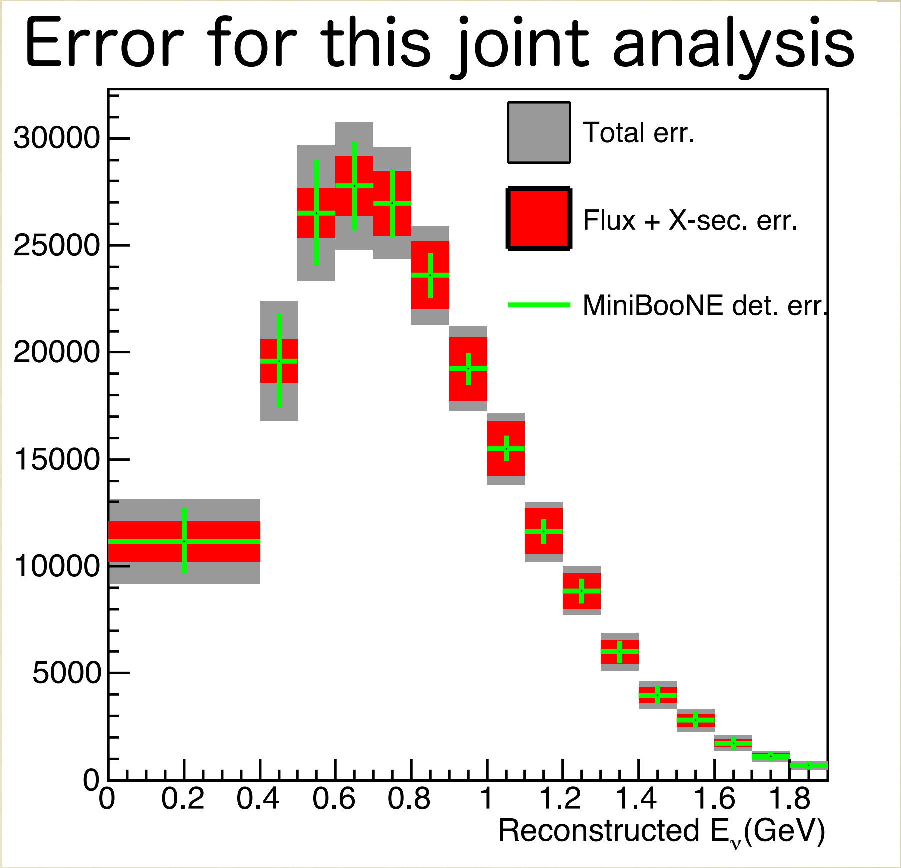
Carefully estimated these errors

MiniBooNE prediction

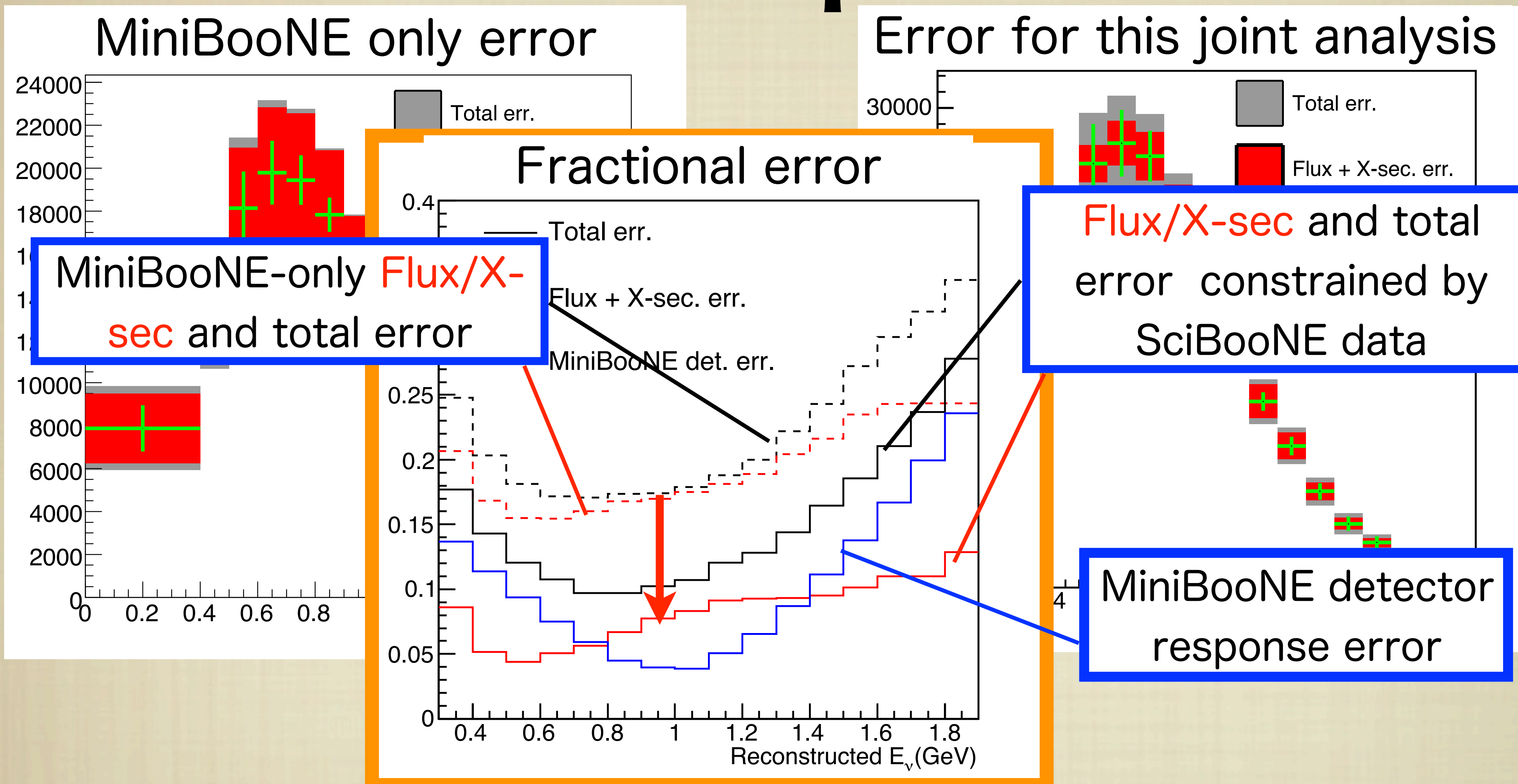


MiniBooNE prediction





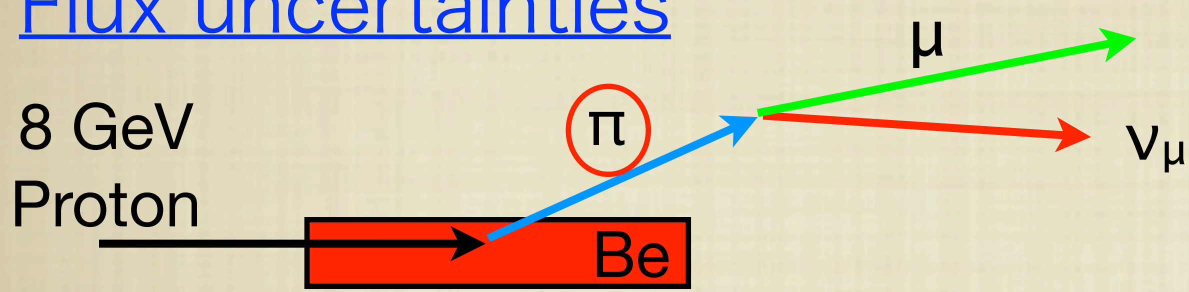
MiniBooNE prediction



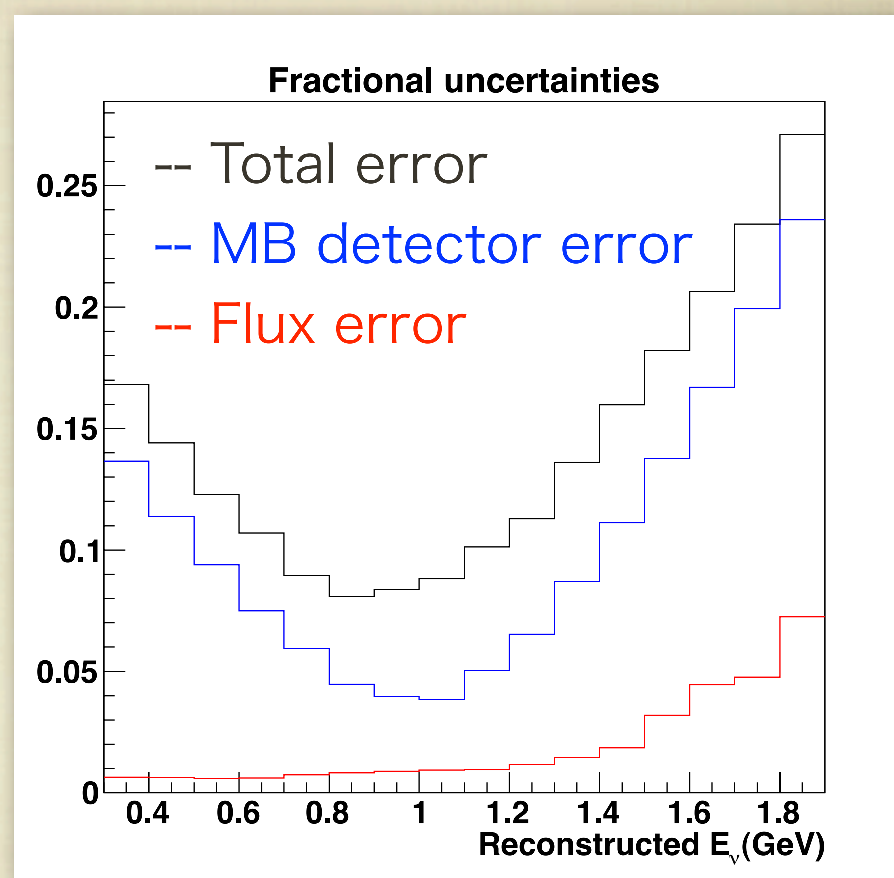
Successfully reduced flux and cross section errors to the same level of the MiniBooNE detector response errors.

Systematic uncertainties(1)

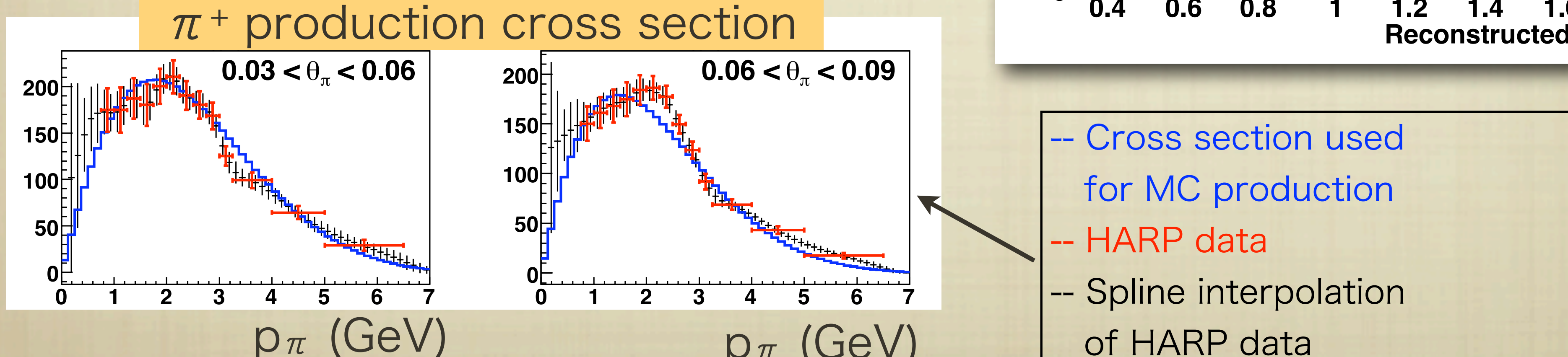
Flux uncertainties



- Use HARP p-Be interaction measurement uncertainty for the error analysis.
- Become negligible after taking ratio between SciBooNE and MiniBooNE

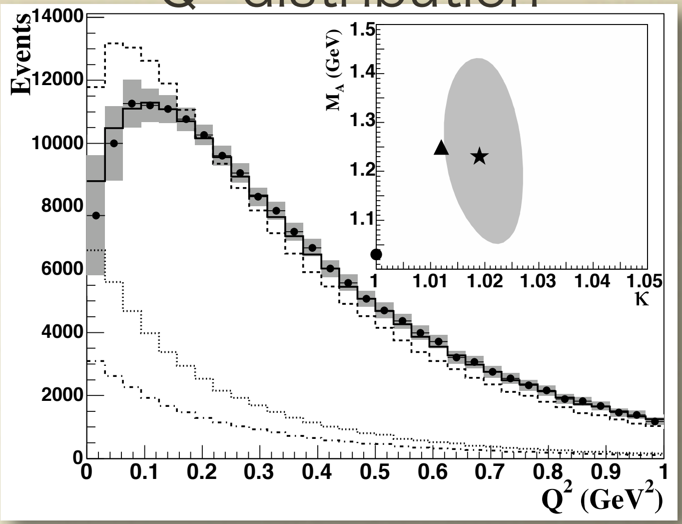


π^+ production cross section



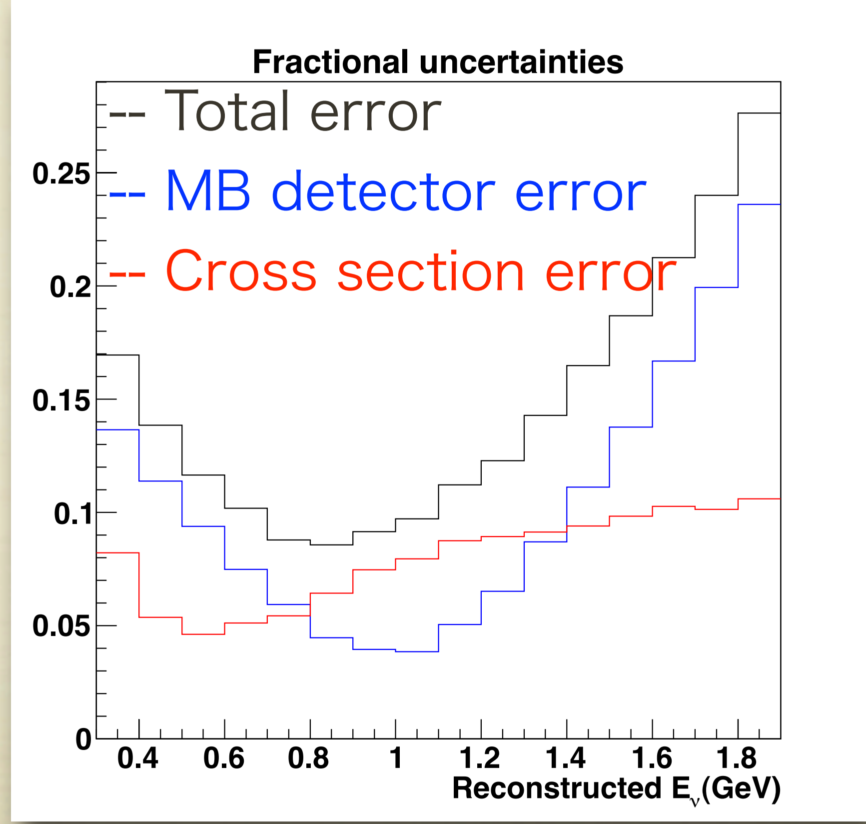
Systematic uncertainties (2)

MiniBooNE CCQE sample
Q^2 distribution

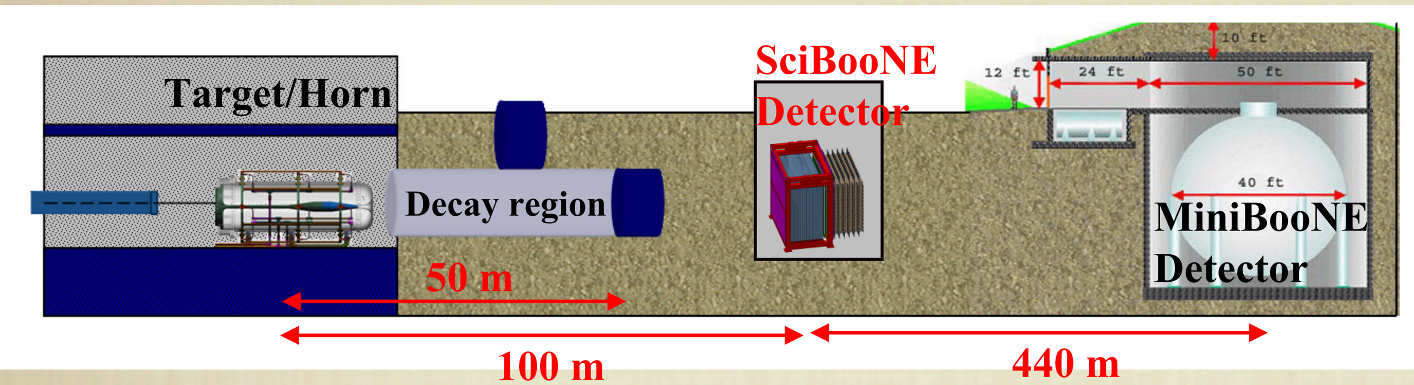


Cross section uncertainties

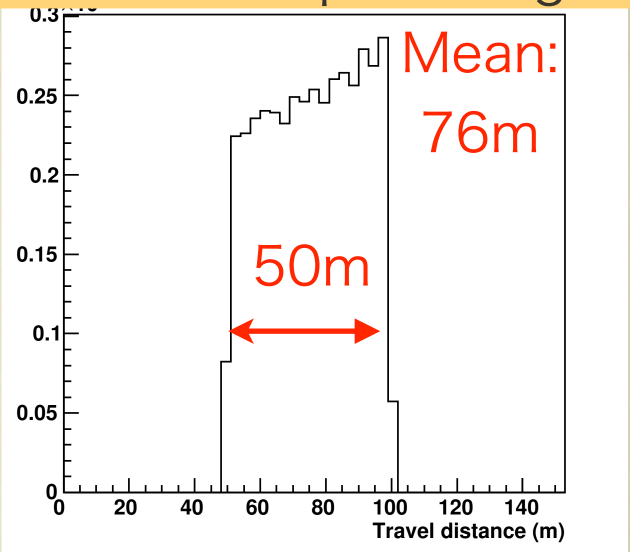
- Variation of Q^2 (muon angle) distribution can change relative acceptance.
  - SciBooNE: forward muon only
  - MiniBooNE: isotropic acceptance.
- The major source of the systematic error, together with the detector response error.



Predicting the oscillation signal

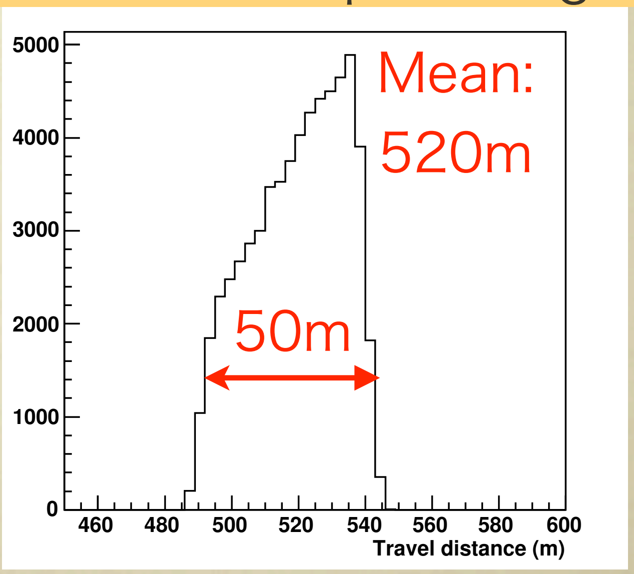


SciBooNE ν path-length



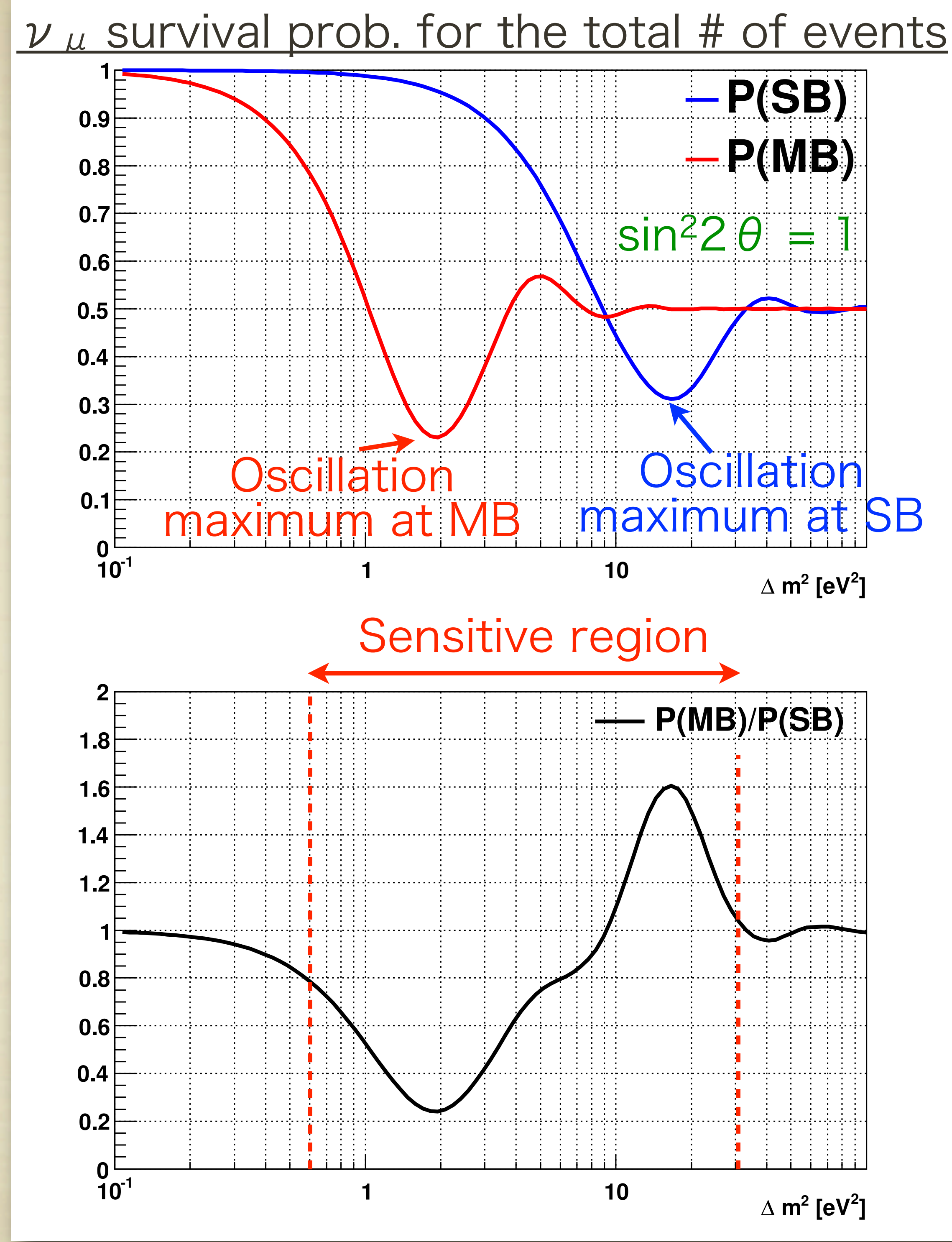
- Mean ν path-length for SciBooNE events: ~76m
- Mean ν path-length for MiniBooNE events: ~520m
- Each has 50m spread due to the finite length of the decay volume
- We take all the three effects into account:
  - Oscillation at SciBooNE
  - Oscillation at MiniBooNE
  - Smearing effect due to 50m spread

MiniBooNE ν path-length



Oscillation probability

- General behavior
  - Oscillation reaches maximum at the first oscillation peak.
  - Then washes out at high Δm^2 by integrating over neutrino energy.
- Since we compare the MB flux with SB, P(MB)/P(SB) is the expected signal.
- Sensitive to oscillations at $0.5 < \Delta m^2 < 30$ eV^2.



Oscillation fit

- Test oscillation hypothesis between 2 flavors, and scan over (Δm^2, $\sin^2 2\theta$) plane.

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

- Evaluate

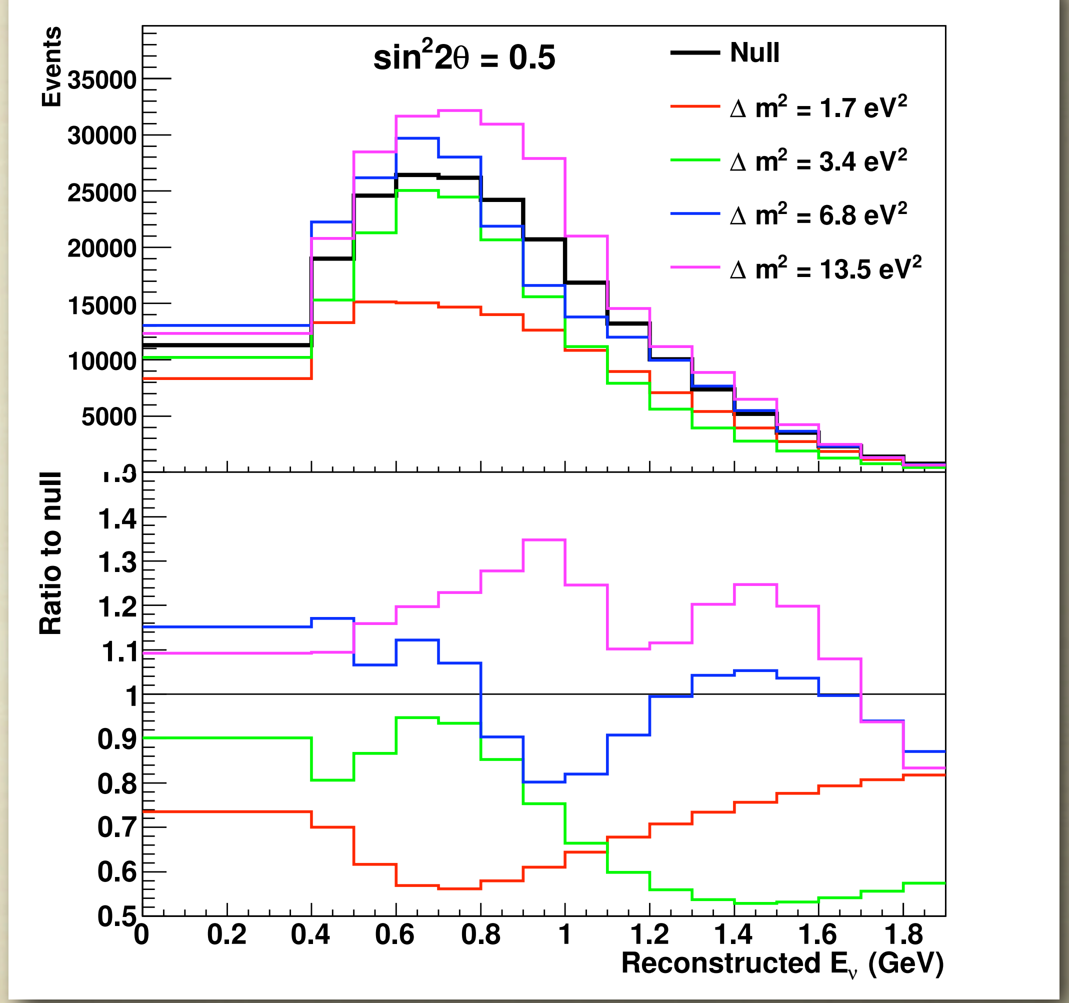
$$\Delta\chi^2 = \chi^2(\text{each point}) - \chi^2(\text{best})$$

$$\chi^2 = \sum_{jk}(M_j^{obs} - M_j^{pred})V_{jk}^{-1}(M_k^{obs} - M_k^{pred})$$

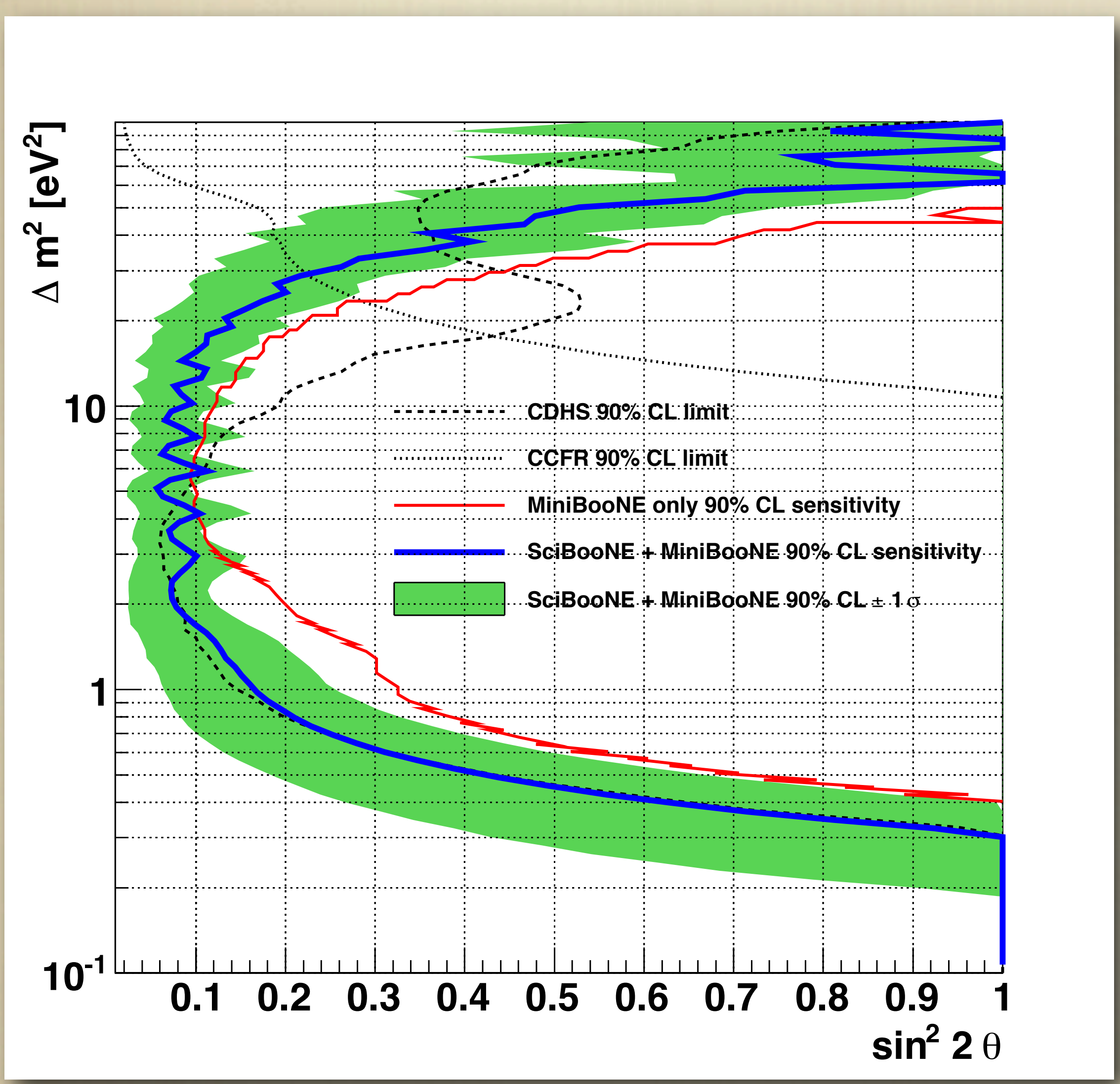
M^{obs}: Data
M^{pred}: Prediction
(function of osc. parameter)
V: Covariance matrix

- Use Feldman-Cousins method to find the confidence level for the obtained $\Delta\chi^2$ values.

MiniBooNE E_ν(rec) prediction



Sensitivity



- Sensitivity reach to $\sin^2 2\theta$ ~0.1 at $1 < \Delta m^2 < 20$ eV^2
- Significantly improved from MiniBooNE-only analysis.
- Achieved world best sensitivity at $0.5 < \Delta m^2 < 30$ eV^2

Analysis Overview

Two independent analyses

Spectrum fit

SciBooNE data

↓ Spectrum fit

CC interaction rate measurement

↓

MiniBooNE rec. E_ν prediction

↕ Oscillation Fit

MiniBooNE rec. E_ν data

Advantage:
Decouple oscillation fit from constraint.
Observe the amount of constraint.

Simultaneous fit

SB + MB Rec. E_ν Data

↕ Oscillation Fit

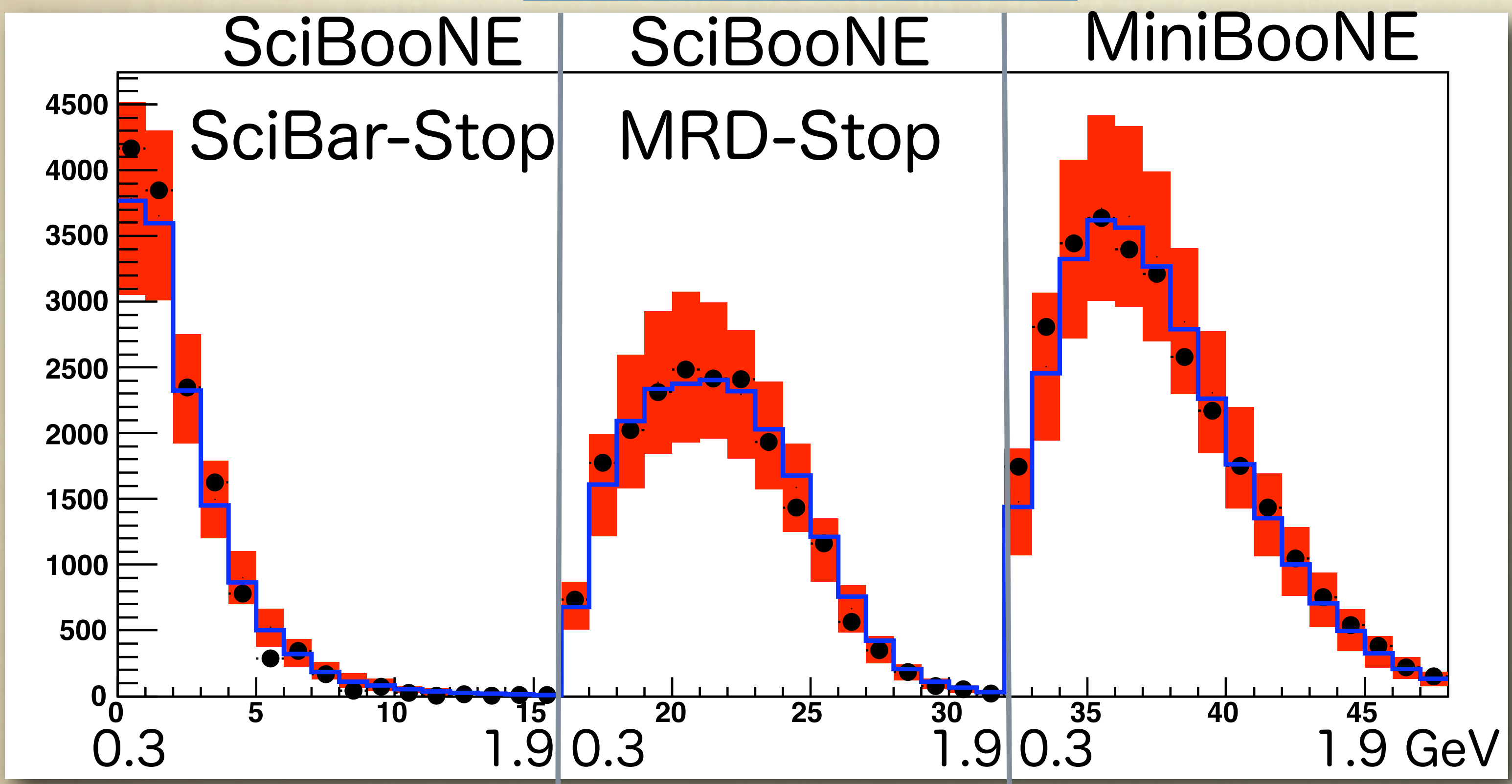
SB + MB Rec. E_ν Prediction

Advantage:
Direct fit for disappearance in SciBooNE and MiniBooNE.
Correlation between the two constrain systematic error.

Simultaneous Fit

- Fit reconstructed E_ν distributions from SciBar-stopped, MRD-stopped and MiniBooNE samples simultaneously.
  - 16 bins/sample x 3 sample = 48 bins
- All bin-to-bin correlation is included into the fit.
  - Off-diagonal elements are strongly correlated.

Reconstructed E_ν



Fake Data
MC with error (Diagonal part)

* MiniBooNE distribution is scaled by ~1/7

Simultaneous Fit (cont'd)

- MC prediction is renormalized by the number of events in SciBooNE.
- Evaluate

  $\Delta\chi^2 = \chi^2(\text{each point}) - \chi^2(\text{best})$

$$\chi^2 = \sum_{i,j}^{BINS} (d_i - Np_i) {M_{ij}}^{-1} (d_j - Np_j)$$

d_i: Data

p_i: Prediction (function of osc. parameter)

M_{ij}: 48x48 covariance matrix

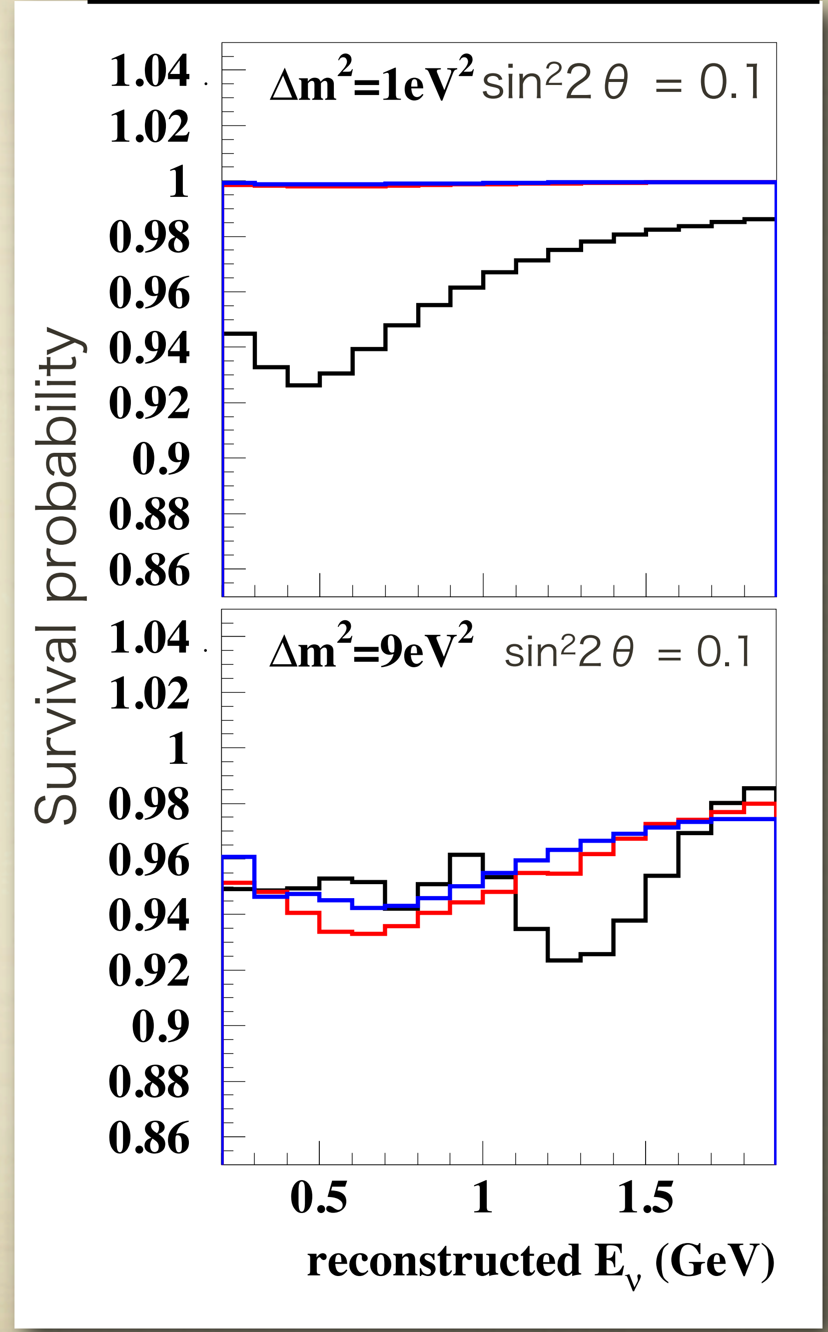
N: Renormalization factor

- Again, Feldman-Cousins's method is used to determine the CLs.

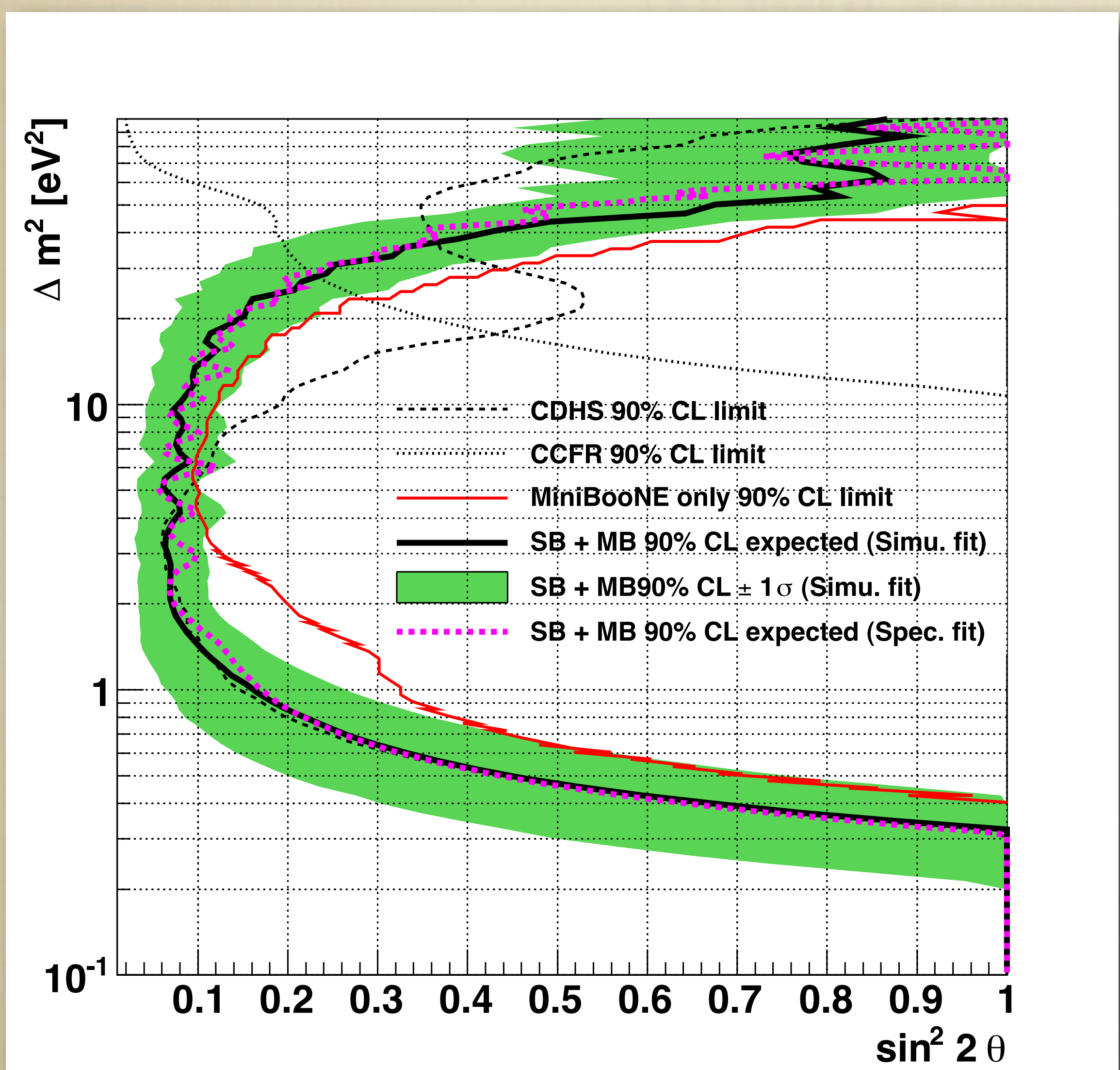
-- SciBooNE SciBar-stoped

-- SciBooNE MRD-stopped

-- MiniBooNE



Simultaneous fit sensitivity



- **Sensitivities of the two analysis method are (roughly) same.**
- Simultaneous fit sensitivity curve is smoother because of smaller binning effect than the spectrum fit analysis.

Results

Spectrum fit result

Fit both MiniBooNE new and old data

Best: $\Delta m^2 = 41.7\ \mathrm{eV}^2$, $\sin^2 2\theta = 0.51$

$\chi^2(\mathrm{null}) = 41.5/32(\mathrm{DOF})$

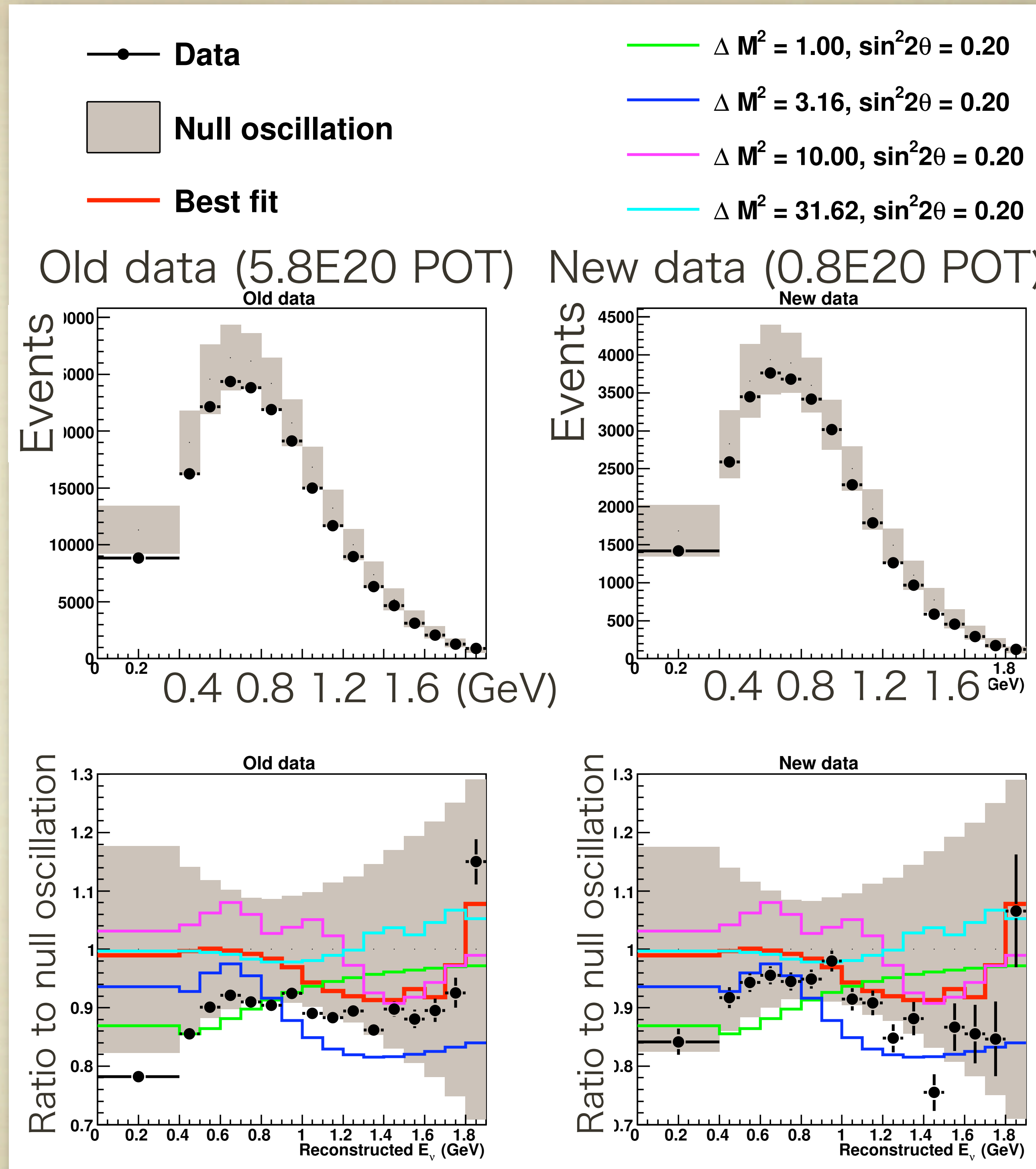
$\chi^2(\mathrm{best}) = 35.6/30(\mathrm{DOF})$

$\Delta\chi^2 = \chi^2(\mathrm{null}) - \chi^2(\mathrm{best}) = 5.9$

$\Delta\chi^2$ (90%CL, null) = 8.4 (estimated by simulation)

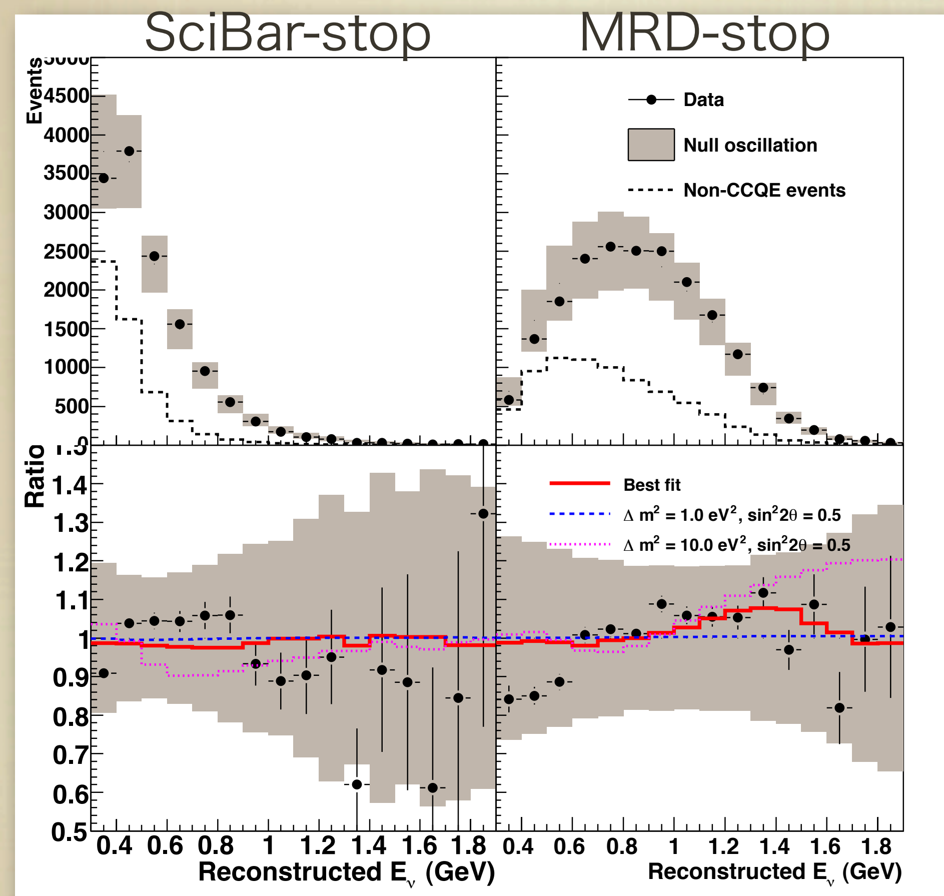
No significant oscillation signal observed.

Small data/MC discrepancy found, but doesn't match oscillation signature.

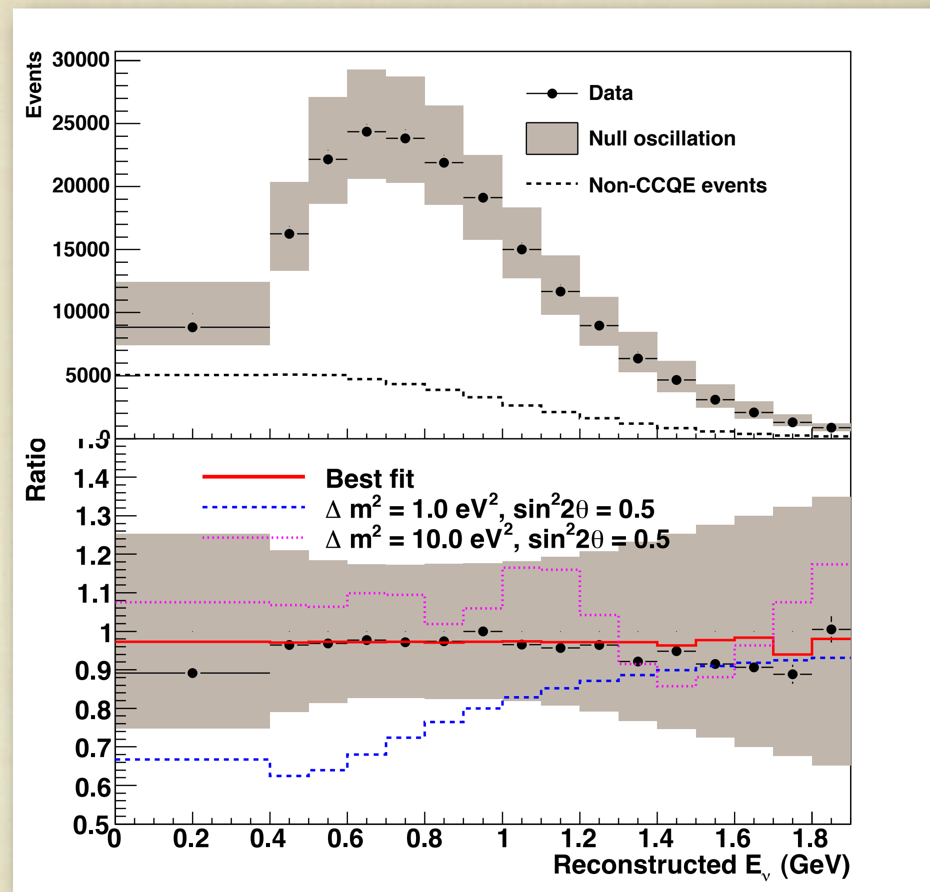


Simultaneous fit result

SciBooNE



MiniBooNE



Best: $\Delta m^2 = 43.7$ eV^2, $\sin^2 2\theta = 0.60$

χ^2(null) = 45.1/48(DOF)

χ^2(best) = 39.5/46(DOF)

$\Delta\chi^2 = \chi^2$(null) - χ^2(best) = 5.6

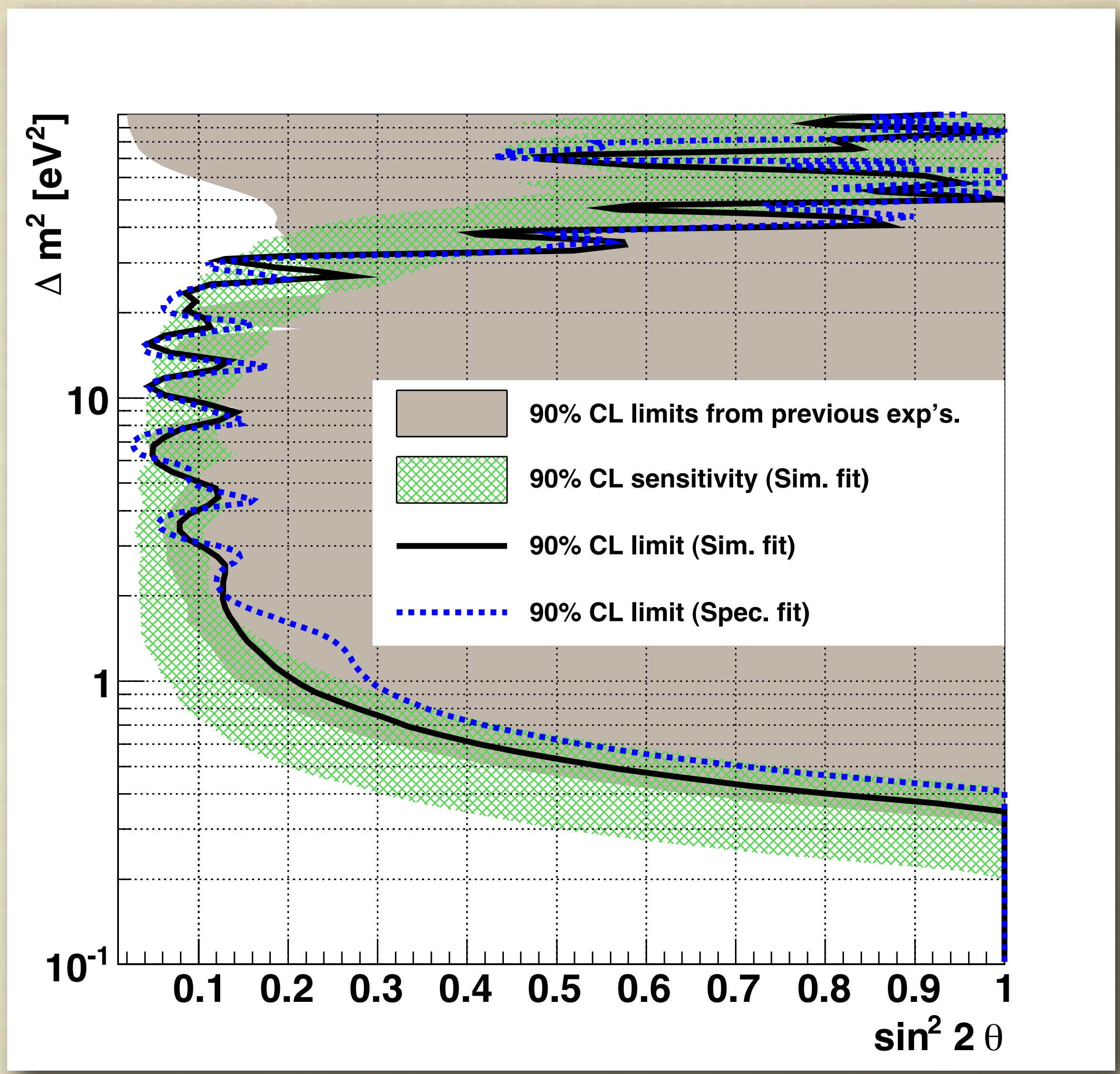
$\Delta\chi^2$ (90%CL, null) = 9.3

(estimated by simulation)

No significant oscillation signal observed, too.

90% CL limit

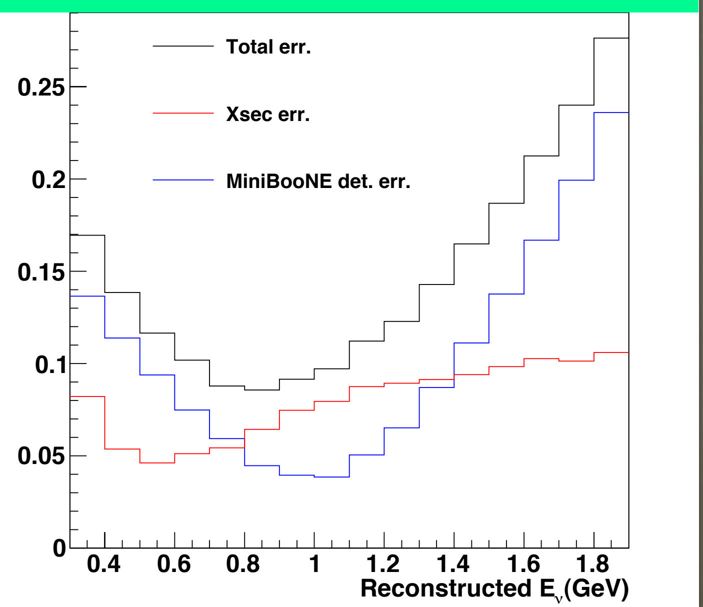
- The observed limits from both analyses are within the ±1 σ band.
  - Another support for null oscillation signal.
- World strongest limit at $10 < \Delta m^2 < 30$ eV^2



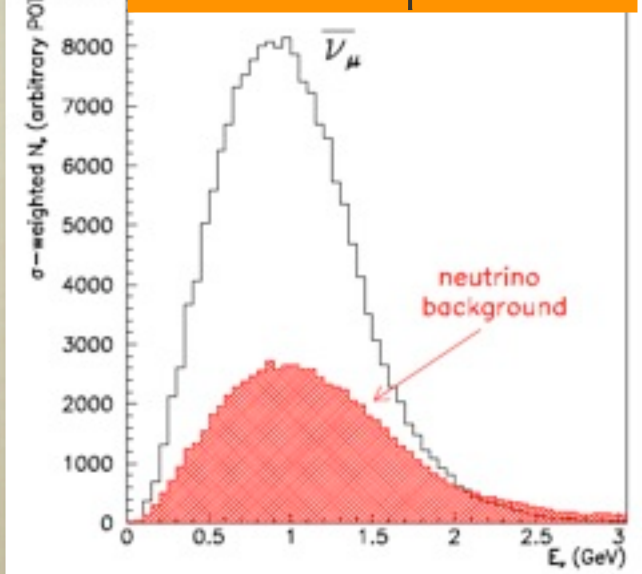
Discussions

- Possible Improvements:
  - Dominant uncertainty: neutrino x-section and MiniBooNE detector response.
  - Further analysis of SciBooNE (and MiniBooNE) data can reduce the cross section errors.
  - To reduce detector error, need identical detectors both at near and far sites.
- Muon antineutrino disappearance analysis ⇐Particularly interesting!
  - This analysis method directly applicable for anti-neutrino analysis.
  - Neutrino-mode result constrain "neutrino background", together with a direct measurement by MiniBooNE (arXiv:1102.164)

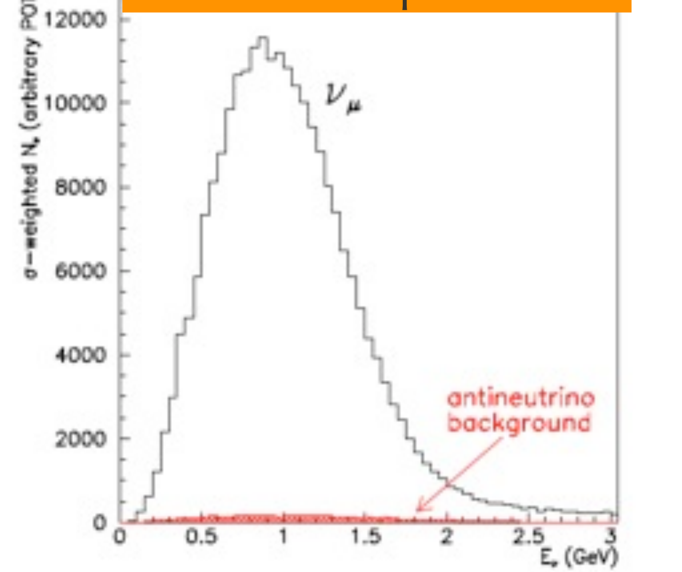
Size of x-sec error at MB



$\overline{\nu}$ mode spectrum



ν mode spectrum



Conclusions

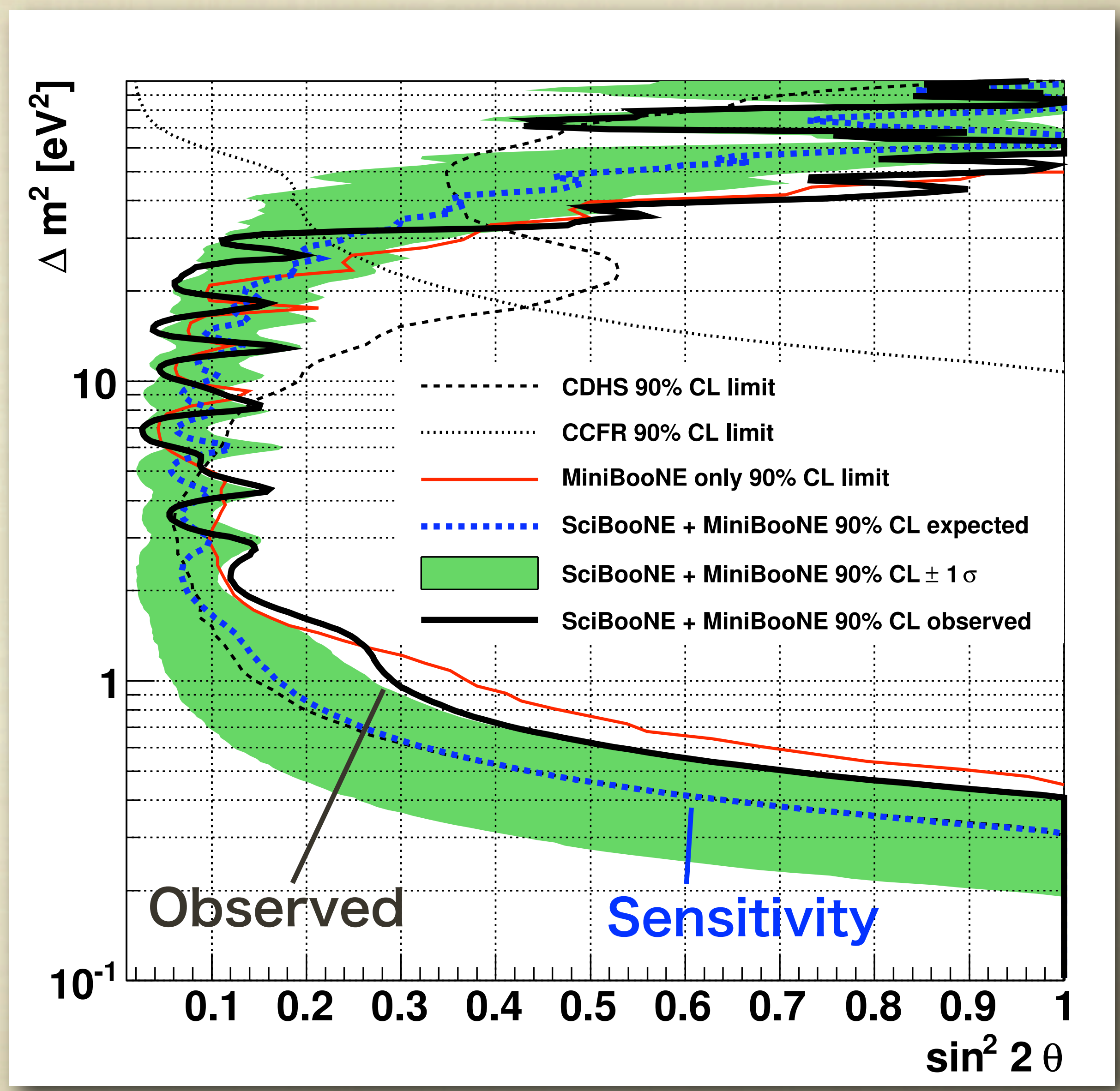
- A joint search for muon neutrino disappearance at $\Delta m^2 \sim 1 eV^2$ with SciBooNE and MiniBooNE is presented.
- Two independent analyses performed; both showed consistent results.
  - Achieved the world best sensitivity at $0.5 < \Delta m^2 < 30\ eV^2$
  - No significant oscillation signal found
  - Set the best 90%CL limit at $10 < \Delta m^2 < 30\ eV^2$
- Preparing for publication of this result.

- Stay tuned for a forthcoming joint muon anti-neutrino disappearance analysis!

Backup Slides

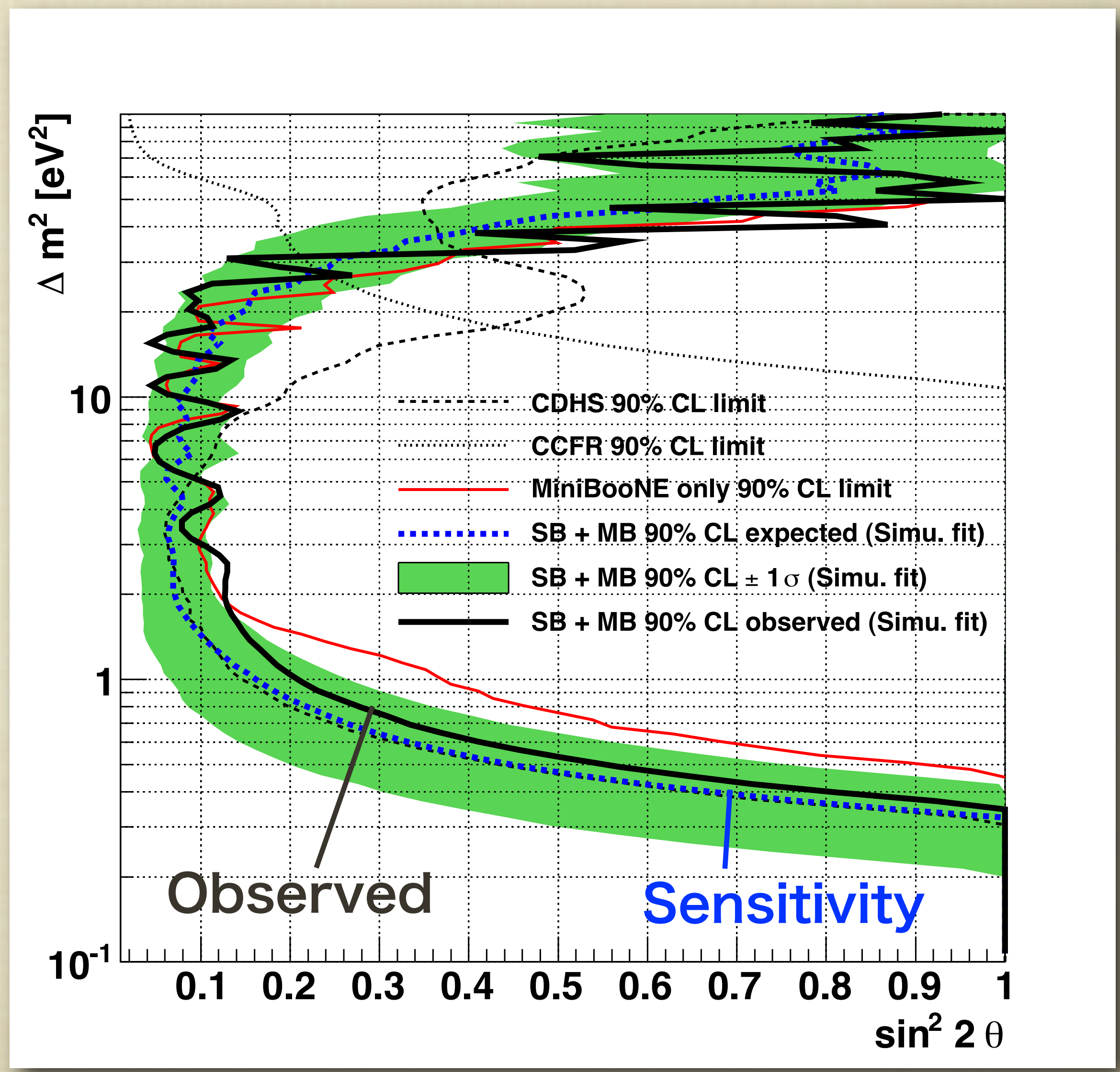
90% CL limit from spectrum fit

- The observed limits are within the ±1 σ band.
  - Another support for null oscillation signal.
- World strongest limit at $10 < \Delta m^2 < 30$ eV^2
  - Constrain sterile neutrino mixing parameters.



90% CL limit from simultaneous fit

- The observed limits are within the ±1 σ band.
  - Another support for null oscillation signal.
- World strongest limit at $10 < \Delta m^2 < 30$ eV^2
  - Constrain sterile neutrino mixing parameters.



List of systematic uncertainties

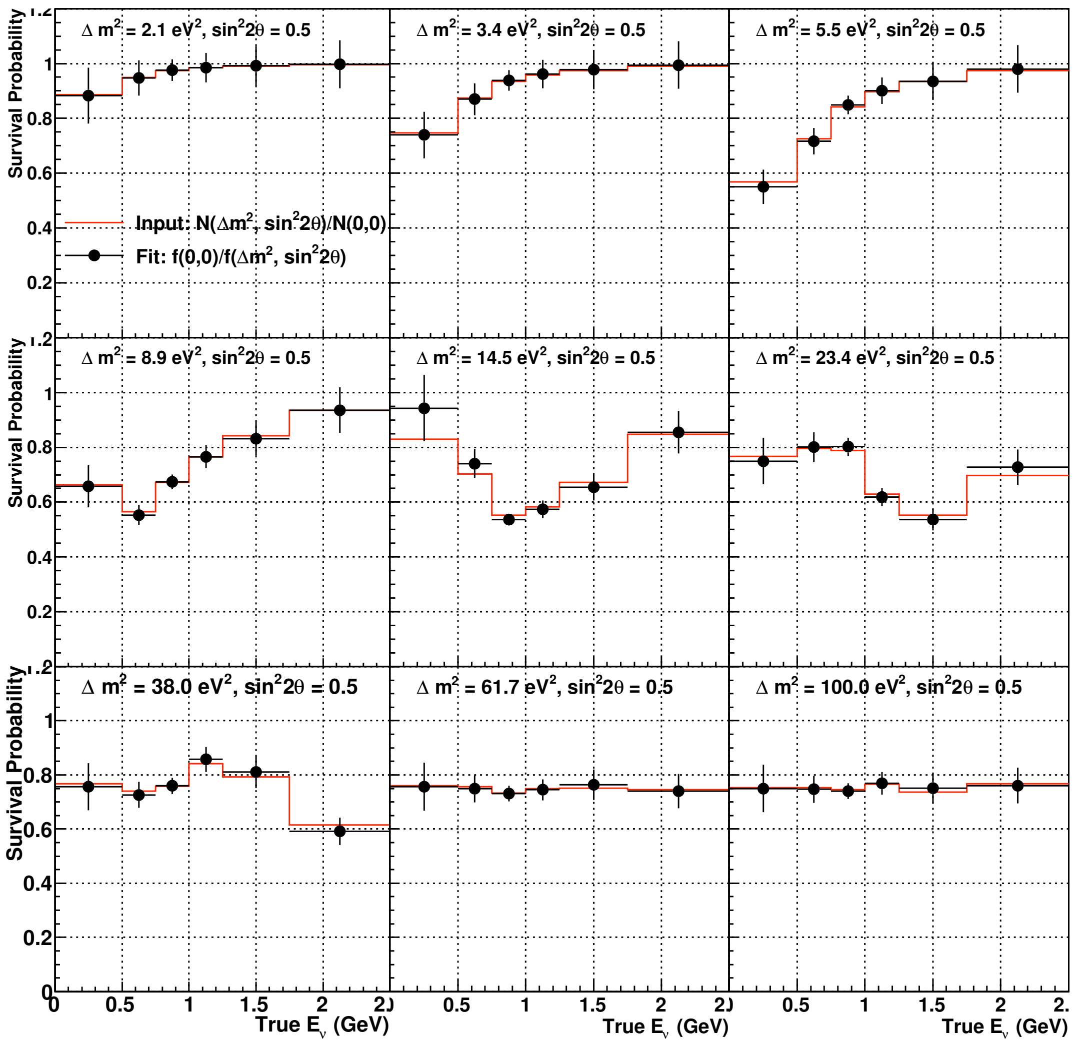
TABLE VIII. List of systematic uncertainties considered.

Category	Error Source	Variation	Description
(i) Flux	π^+/π^- production from p-Be interaction	Spline fit to HARP data [19]	Sec. II B
	K^+/K^0 production from p-Be interaction	Tables VIII and IX in Ref. [21]	Sec. II B
	Nucleon and pion interaction in Be/Al	Table XIII in Ref. [21]	Sec. II B
	Horn current	± 1 kA	Sec. II B
	Horn skin effect	Horn skin depth, ± 1.4 mm	Sec. II B
	Number of POT	$\pm 2\%$	Sec. II B
(ii) Neutrino interaction	Fermi surface momentum of carbon nucleus	± 30 MeV	Sec. III B 1
	Binding energy of carbon nucleus	± 9 MeV	Sec. III B 1
	CC-QE M_A	± 0.22 GeV	Sec. III B 1
	CC-QE κ	± 0.022	Sec. III B 1
	CC-1π M_A	± 0.28 GeV	Sec. III B 2
	CC-1π Q^2 shape	Estimated from SciBooNE data	Sec. III B 2
	CC-coherent-π M_A	± 0.28 GeV	Sec. III B 3
	CC-multi-π M_A	± 0.52 GeV	Sec. III B 4
(iii) Intra-nuclear interaction	Δ re-interaction in nucleus	± 100 %	Sec. III B 2
	Pion charge exchange in nucleus	± 20 %	Sec. III B 5
	Pion absorption in nucleus	± 35 %	Sec. III B 5
	Proton re-scattering in nucleus	± 10 %	Sec. III B 5
	NC/CC ratio	± 20 %	Sec. III B 5
(iv) Detector response	PMT 1 p.e. resolution	± 0.20	Sec. II D
	Birk's constant	± 0.0023 cm/MeV	Sec. II D
	PMT cross-talk	± 0.004	Sec. II D
	Pion interaction cross section in the detector material	± 10 %	Sec. II D
	dE/dx uncertainty	$\pm 3\%$(SciBar,MRD), $\pm 10\%$(EC)	Sec. II D
	Density of SciBar	± 1 %	Sec. II C
	Normalization of interaction rate at the EC/MRD	± 20 %	Sec. III A
	Normalization of interaction rate at the surrounding materials	± 20 %	Sec. III A

Rate normalization factors from SciBooNE spectrum fit

Energy region (GeV)	ν_μ CC rate normalization factor NEUT	NUANCE
0.25 - 0.50	1.04 ± 0.20	1.65 ± 0.22
0.50 - 0.75	1.03 ± 0.11	1.31 ± 0.11
0.75 - 1.00	1.23 ± 0.08	1.36 ± 0.08
1.00 - 1.25	1.29 ± 0.10	1.38 ± 0.09
1.25 - 1.75	1.19 ± 0.11	1.36 ± 0.12
1.75 -	0.79 ± 0.08	0.90 ± 0.09

Test of SB spectrum fit with oscillation effects



Black points: fit result

Red lines: input value